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International Agreement Report

Plant Application with TRACE Code of the PKL III G1 Test Series. Study on Heat Transfer Mechanisms in the SG in Presence of Nitrogen, Steam and Water as a Function of the Primary Coolant Inventory in Single & Double Loop Operation

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ABSTRACT

The main goal of this report is to explain a PWR plant application of the G1 tests series carried out in the PKL III facility through a TRACE model. With this purpose, the experimental data and TRACE V5.0p2 simulation results of PKL III G1.1 and G1.2 tests are used. Then, two TRACE simulations have been carried out, one for a commercial NPP model and the other for an own PKL facility model. The PKL III G1 test series are focused on the occurrence of boron dilution processes following the loss of RHRS during ¾-loop operation. Test G1.1 features a systematic study on heat transfer in SG U-tubes in presence of nitrogen, steam and water with variable Primary Coolant Inventory (PCI) in the PKL III test facility with a single loop configuration. While G1.2 test as the same purpose than G1.1 but with two loops in operation. A goal of this report is to analyse the capacity of TRACE V5.0p2 code to precisely simulate thermal stratification and natural circulation of both single and two-phase flow inside the whole primary circuit of PKL facility.

FOREWORD

Thermalhydraulic studies play a key role in nuclear safety. Important areas where the significance and relevance of TH knowledge, databases, methods and tools maintain an essential prominence, are among others:

- assessment of plant modifications (e.g., Technical Specifications, power uprates, etc.);
- analysis of actual transients, incidents and/or start-up tests;
- development and verification of Emergency Operating Procedures;
- providing some elements for the Probabilistic Safety Assessments (e.g., success criteria and available time for manual actions, and sequence delineation) and its applications within the risk informed regulation framework;
- training personnel (e.g., full scope and engineering simulators); and/or
- assessment of new designs.

For that reason, the history of the involvement in Thermalhydraulics of CSN, nuclear Spanish Industry as well as Spanish universities, is long. It dates back to mid 80's when the first serious talks about Spain participation in LOFT-OCDE and ICAP Programs took place. Since then, CSN has paved a long way through several periods of CAMP programs, promoting coordinated joint efforts with Spanish organizations within different periods of associated national programs (i.e., CAMP-España).

From the CSN perspective, we have largely achieved the objectives. Models of our plants are in place, and an infrastructure of national TH experts, models, complementary tools, as well as an ample set of applications, have been created. The main task now is to maintain the expertise, to consolidate it and to update the experience. We at the CSN are aware on the need of maintaining key infrastructures and expertise, and see CAMP program as a good and well consolidated example of international collaborative action implementing recommendations on this issue.

Many experimental facilities have contributed to the today's availability of a large thermal-hydraulic database (both separated and integral effect tests). However there is a continuous need for additional experimental work and code development and verification, in areas where no emphasis have been made along the past. On the basis of the SESAR/FAP[1] reports "*Nuclear Safety Research in OECD Countries: Major Facilities and Programmes at Risk" (SESAR/FAP, 2001)* and its 2007 updated version "*Support Facilities for Existing and Advanced Reactors (SFEAR) NEA/CSNI/R(2007)6"*, CSNI is promoting since the beginning of this century several collaborative international actions in the area of experimental TH research. These reports presented some findings and recommendations to the CSNI, to sustain an adequate level of research, identifying a number of experimental facilities and programmes of potential interest for present or future international collaboration within the nuclear safety community during the coming decade. The different series of PKL, ROSA and ATLAS projects are under these premises.

CSN, as Spanish representative in CSNI, is involved in some of these research activities, helping in this international support of facilities and in the establishment of a large network of international collaborations. In the TH framework, most of these actions are either covering not

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[1] SESAR/FAP is the *Senior Group of Experts on Nuclear Safety Research Facilities and Programmes* of NEA Committee on the Safety of Nuclear Installations (CSNI).

enough investigated safety issues and phenomena (e.g., boron dilution, low power and shutdown conditions, beyond design accidents), or enlarging code validation and qualification data bases incorporating new information (e.g., multi-dimensional aspects, non-condensable gas effects, passive components).

This NUREG/IA report is part of the Spanish contribution to CAMP focused on:

- Analysis, simulation and investigation of specific safety aspects of PKL/OECD ROSA/OECD and ATLAS/OECD experiments.
- Analysis of applicability and/or extension of the results and knowledge acquired in these projects to the safety, operation or availability of the Spanish nuclear power plants.

Both objectives are carried out by simulating the experiments and conducting the plant application with the last available versions of NRC TH codes (RELAP5 and/or TRACE).

On the whole, CSN is seeking to assure and to maintain the capability of the national groups with experience in the thermalhydraulics analysis of accidents in the Spanish nuclear power plants. Nuclear safety needs have not decreased as the nuclear share of the nation's grid is expected to be maintained if not increased during next years, with new plants in some countries, but also with older plants of higher power in most of the countries. This is the challenge that will require new ideas and a continued effort.

Rosario Velasco García, CSN Vice-president

Nuclear Safety Council (CSN) of Spain

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EXECUTIVE SUMMARY

This report develops the plant application of PKL III G1 experimental series. With this purpose, throughout this document a comparison of the PKL experimental data against the results obtained with two TRACE models, one for the own PKL facility and another one for a nuclear power plant, have been carried out. The TRACE simulations were run using the SNAP v2.0.4 interface and the TRACE v5.0 code.

The PKL facility is owned and operated by AREVA NP and is located in Erlangen, Germany. The PKL-III G test program investigates safety issues relevant for current pressurized water reactor (PWR) plants as well as for new PWR design concepts, focusing on complex heat transfer mechanisms in the steam generators and boron precipitation processes under postulated accident situations. Specifically, the first test series G1 focused in systematically investigating the heat transfer mechanisms in the steam generators in the presence of nitrogen, steam and water, with two experiments being conducted: G1.1 (one loop configuration) and G1.2 (two loop configuration).

The PKL facility models the entire primary side and significant parts of the secondary side of a pressurized water reactor at a height scale of 1:1, with volumes, power ratings and mass flows being scaled with a ratio of 1:145. The experimental facility consists of four primary loops with circulation pumps and steam generators (SGs) arranged symmetrically around the reactor pressure vessel (RPV). The investigations carried out in this facility encompass a very broad spectrum, from accident scenario simulations with large, medium, and small breaks, over the investigation of shut-down procedures after a wide variety of accidents, to the systematic investigation of complex thermal-hydraulic phenomena, having been in operation since 1977.

The objective of this document is to carry out an application to a NPP of experiments made in an experimental facility. In order to achieve this objective, the comparison of the code calculations of a real NPP against the experimental data and the simulation results of PKL facility are shown along this document. The main features tested with these tests are the TRACE's capability to model heat transfers at atmospheric pressure in presence of nitrogen (modelled as air in the TRACE model, due to its similarity with pure nitrogen), water and steam in the U-tubes and the coolant transfer phenomena inside the U-tubes observed in previous tests, as well as assessing TRACE code precision. As a secondary objective, this report assesses TRACE capability to correctly predict boron concentration variations during several consecutive evaporations and condensations of primary coolant liquid. During all tests the pressurizer (PRZ) was permanently isolated from the primary circuit, thus not being part of the primary side volumes.

Prior to the transient phase start, a conditioning phase was conducted, in order to achieve the initial test conditions and the initial inventory status. The preliminary test phase started with a complete filling with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure. In which only loop 1 was filled in test G1.1, whereas loops 1 and 2 were filled for test G1.2. Then proceeding with a slow drain of the primary inventory down to ¾-loop, coupled with a constant feed of N_2 to the primary circuit via the PRZ valve station, thus replacing the void volumes resulting from the drainage. After completing the decrease of primary coolant inventory, rod bundle power was decreased to 200 kW in order to simulate the decay heat in the core, accounting to 0.6% of full load thermal power, including compensation for heat losses. After fixing core thermal power, the system remains under this conditions enough time to reach the steady-state conditions. During this time, core power is removed from the system using the residual heat removal system (RHRS).

Start of test (SOT) begin with the shut-down of RHRS, it causes:

> Heat-up of core inventory.

> Start of steam formation in the core (approximately 10 min after shut-down of RHRS).

> Frothing of core inventory.

Both tests were started at steady state conditions with alevel of the primary coolant inventory of ¾-loop with the RHRS engaged. Throughout the tests, the secondary pressure was controlled at 2 bars by the Main Steam Relief Valve (MSRV). Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DownComer-pipes (DC-pipes). In this way, the additional coolant was injected into the subcooled fluid, not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/refilling procedures.

ACKNOWLEDGMENTS

The thermal-hydraulic and nuclear engineering group of the UPV is indebted to the management board of the PKL III project and to the people of the Thermal-Hydraulics Safety Research Group of AREVA. The authors are grateful to UNESA and CSN, who financed this study and help to develop this report. We also thank to the “Grupo de Análisis Dinámico de Sistemas Energéticos del Instituto de Técnicas Energéticas de la Universidad Politécnica de Cataluña”, who provided the initial TRACE model of the PKL III facility and many interesting suggestions on the improvement of the model.

ABBREVIATIONS AND ACRONYMS

B	Boron ([B]: boron concentration, ppm)
CCFL	CounterCurrent Flow Limitation
CI	Coolant Inventory
CL	Cold Leg
CM	Coolant Mass
COMBO	Continuous Measurement of Boron Concentration
CSN	Spanish Nuclear Regulatory Commission
CVCS	Chemical/Volume Control System
Δp	Pressure difference in bar, Pa
DC	Downcomer
DCT	Downcomer Tube/pipe
DCV	Downcomer Vessel
EOT	End Of Test
HL	Hot Leg
ITF	Integral Test Facility
LOCA	Loss of Coolant Accident
$\dot{m}$	kg/s Mass flow
max	Maximum
MCP	Main Coolant Pump
min	Minimum
MS	Main Steam
MSRV	Main Steam Relief Valve
NC	Natural Circulation
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plants
OECD	Organization for Economic Cooperation and Development
p	Pressure in bar, Pa
P	Power in kW
PCI	Primary Coolant Inventory
PKL	Test facility, (German acronym for “Primärkreislauf”, means: primary circuit)
prim	Primary
PRZ	Pressurizer
PS	Pump Seal
PWR	Pressurized Water Reactor
ρ	Density in kg/m^3
RC	Reflux-Condenser
RCL	Reactor Coolant Line
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
RPV	Reactor Pressure Vessel
sec	Secondary
SG	Steam Generator
SOT	Start Of Test
STP	Standard Temperature and Pressure conditions
t	Time in s
T	Temperature in °C, K
TRACE	TRAC-RELAP Advanced Computational Engine

UNESA	Asociación Española de la Industria Eléctrica
UPTF	Upper Plenum Test Facility

1 INTRODUCTION

Extensive study has been carried out in recent decades related with the knowledge and development of thermal-hydraulic codes. These codes are intended to simulate the behaviour of a reactor during transients and accidents. The agreements between the NRC of United States and CSN of Spain in the area of research in nuclear security have resulted in access of CSN to the best-estimate codes under development of the NRC, such as the TRACE code. One of the sections of this agreement involves conducting different transients with the TRACE code and its comparison with the results of experimental facilities. In particular, the present study was carried out as a contribution to the OCDE international collaborative research project PKL. The Spanish contribution was coordinated by the Spanish Nuclear Regulatory Commission (CSN) with the contribution of the Spanish Electricity Producers Association (UNESA). A consortium formed by the CSN, several Spanish Technical Universities and UNESA developed the Spanish participation in the project that was coordinated by the CSN and a steering committee.

This study fits into the scope of development of these codes and is integrated into the aforementioned research project, under this project the simulation of the PKL III G1.1 and G1.2 experiments were carried out using the SNAP v2.0.4 interface and the TRACE v5.0 code. Such experiments have, as main objective, the study of residual heat removal from the steam generators in the presence of non-condensable gases (G1.1 with a single steam generator active, while for test G1.2 with two active loops).

Transient experiments begin with the shut-down of the residual heat removal system (RHRS) followed by extractions of coolant inventory in the primary circuit, these extractions have as a consequence the partially core uncovery for the test G1.1, while this core uncovery does not happen for the test G1.2. Then the core level rises due to a series of stepwise injections of coolant inventory. The situation described causes the heat exchange of the U-tubes (G1.1 one active SG, G1.2 two active SGs) to present active and passive areas, which is a very difficult situation to be simulated by current thermal-hydraulic codes. In conclusion, the fundamental objectives are, on the one hand, analyse the capability of the TRACE code to simulate the situation described above, having obtained acceptable results, thereby contributing to the improvement and testing of the code. And secondly, the other objective is testing the code capability in modelling a commercial PWR plant. Checking the similarities between the experimental results and those obtained by the code with the PWR plant model and with the own PKL model. Thus, with the ultimate intention of corroborate the applicability of the TRACE model of a commercial NPP, in order to obtain reliable results for the different possible transients under study.

2 DESCRIPTION OF THE PKL FACILITY

The integral test facility PKL (Figure 2-1), which is operated at the Technical Center of Framatome ANP, is a mock-up of a 1300MW class PWR (Kremin, Limprecht et al., 2001). It is used for research into the behavior of the thermal-hydraulic system under accident situations with and without loss of coolant. The test facility simulates the entire primary side with four loops and the essential parts of the secondary side. In view of the importance of gravity during accident situations, all elevations of the test facility correspond to actual reactor dimensions. The overall volume and power scaling factor is 1:145. In order to account for important phenomena in the hot legs such as flow separation and counter current flow limitation, the design of the hot leg bases on the conservation of the Froude number whereas also the results of the experiments in the 1:1 scaled UPTF were taken into consideration.

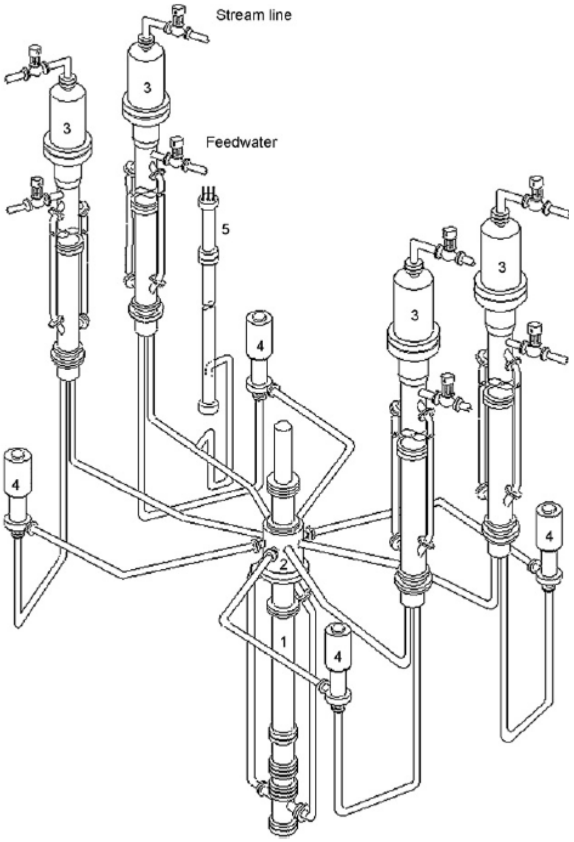

Figure 2-1 PKL Facility. (1) Reactor Pressure Vessel; (2) Downcomer; (3) Steam Generator; (4) Pump; (5) Pressurizer. Volume: 1:145; Elevations: 1:1; Max. Pressure: 45 Bars; Max. Power 2.5MW

The reactor core and the steam generators are simulated as a “section” from the actual system, in other words, full-scale rods and U-tubes are used. The number of rods and tubes has been scaled. The reactor pressure vessel has been modeled by scaling the cross sectional area preserving the full height of the core and the upper and lower plenums. The core is modeled by a bundle of 314 electrically heated rods with a total power of 2.5MW corresponding to 10% of the scaled nominal power. The reactor pressure vessel (RPV) downcomer is modeled as an annulus in the upper region and continues as two stand pipes connected to the lower plenum. This configuration provides symmetrical connection of the four cold legs to the RPV, reliable determination of flow rates, preservation of frictional pressure losses and does not unacceptably distort the volume/surface ratio. The symmetrical arrangement of the four loops around the RPV means that the requirement for identical piping lengths and hence recirculation period is fulfilled. This configuration enables the individual effects of multiple system failures to be studied as well as other events. Experiments on the behavior of a 3-loop (2-loop) plant can also be conducted by simply isolating one (two) loop(s).

Each of the primary-side loops contains active coolant pumps which are equipped with speed controllers to enable any pump characteristics to be simulated. The four fully scaled steam generators are equipped with prototype tubing (diameter, wall thickness, differing lengths) and tube sheet.

By preserving the frictional pressure losses in the steam generators and in the core region, the integral pressure loss for the entire primary system is also very similar to that of the actual plant. The maximum operating pressure of the PKL facility is 45 bars on the primary side and 60 bars on the secondary. This allows simulation over a wide temperature range.

PKL is also equipped with all relevant safety and operational systems on both the primary and secondary side. On the primary side the following are all simulated: four independent high- and low-pressure safety injection systems connected to both the hot and cold legs, the residual heat removal system, eight accumulators, the pressurizer pressure control system and the chemical and volume control system. On the secondary side, the feedwater system, the emergency feedwater system and the main steam lines, with all control features of the original systems are modeled. For the realistic simulation of secondary-side bleed-and-feed procedures, special care was taken to correctly model the feedwater lines and the feedwater tank with respect to the volume (1:145), the elevations (1:1) and the friction losses (1:1). All these features allow the simulation of a wide spectrum of accident scenarios involving the interaction between the primary and secondary side in combination with various safety and operational systems.

The facility is extensively instrumented with more than 1300 measuring points. Besides conventional measurements (temperature, pressure, etc.), two-phase flow measurements can also be made. In addition, for the test series PKL III E, F and the current series PKL III G, special devices for the detection of boron concentration were installed.

To summarize, the PKL facility is a full-height Integral Test Facility (ITF) that models the entire primary system (four loops) and most of the secondary system (except for turbine and condenser) of a 1300-MW PWR.

The facility includes:

- Reactor Coolant System (RCS)

- Steam Generators (SG’s)

- The interfacing systems on the primary and secondary side and the break.

The RCS includes:

- The upper head plenum, which is cylindrical, full-scale in height and 1:145 in volume.

- The upper plenum, full-scale in height and scaled down in volume.

- The upper head bypass, represented by four lines associated with the respective loops to enable detection of asymmetric flow phenomena in the RCS (e.g., single-loop operation).

- The reactor core model, consisting of 314 electrically heated fuel rods and 26 control rod guide thimbles. The maximum electrical power of the test bundle is 2512 kW.

- The reflector gap, located between the rod bundle vessel and the bundle wrapper (the barrel in the real plant).

- The lower plenum, containing the 314 extension tubes connected with the heated rods. The down-comer pipes are welded on the lower plenum bottom in diametrically opposite position. Two plates are located in this zone: the Fuel Assembly Bottom Fitting and the Flow Distribution Plate.

- The downcomer modeled as an annulus in the upper region and continues as two stand pipes connected to the lower plenum. This configuration, as already mentioned above, permits symmetrical connection of the 4 Cold Legs (CL) to the RPV, preserves the frictional pressure losses.

- The (four) hot legs, designed taking into account the relevance of an accurate simulation of the two phase flow phenomena, in particular CounterCurrent Flow Limitation (CCFL), in the hot leg piping as in the reactor.

- The (four) cold legs, connecting the SG to the Main Coolant Pump (MCP) through the loop seal and the MCP to the DownComer (DC) vessel. The hydrostatic elevations of the loop seals are 1:1 compared with the prototype NPP.

- The (four) MCP, which are vertical single-stage centrifugal pumps.

- The PRZ, full-height and connected through the surge line to the hot leg #2.

- The SG primary side, modeled with vertical U-tube bundle heat exchangers like in the prototype NPP. The scaling factor has been preserved by reducing the number of tubes (28 tubes with seven different lengths).

- The SG (secondary side) is constituted by the tube bundle zone, seal welded hollow fillers (below the shortest tubes), the DC (with the upper zone annular containing the FW ring, the central zone modeled by two tubes outside of the SG housing and the lower zone with annular shape) and the uppermost part of the SG that models the steam plenum.

3 DESCRIPTION OF THE PKL III G1.1 & G1.2 EXPERIMENTAL SERIES

3.1 Test G1.1

3.1.1 Initial Test Conditions

The PKL III G1.1 test was conducted in the PKL facility, this test is focused in the study of the residual heat removal by one steam generator in the presence of non-condensable gases, the other three loops are isolated during test execution.

The initial test conditions were reached at a preliminary stage. This phase began with the complete filling of the entire loop 1 with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure (p_{prim} ~ 1 bar). The slow drain of the primary inventory down to ¾-loop (approximately 1060 kg of residual inventory, i.e., a level of 7.75 meters from the bottom part of the lower plenum) was attended by a constant feed of N_2 to the primary circuit via the PRZ valve station, thereby replacing the void volumes emerging from the drainage. The volume of N_2 fed to the primary circuit was approximately 0.6 m³ at Standard Temperature and Pressure conditions (STP).

After this decrease of the primary coolant inventory, the rod bundle power was set to 200 kW (simulation of the decay heat in the core, resembling 0.6 % of full load thermal power, inclusive compensation for heat losses) and kept constant throughout the test. Until start of test, the core power was removed from the primary circuit via the residual heat removal system (RHRS) engaged in loop 1. The secondary circuit of the active loop was kept at a constant pressure of 2 bars and the liquid level at 12.2 meters throughout the duration of the test. These initial conditions were the operating ones prior to the start of test, SOT. Table 3-1 and Figure 3-1 present this test initial facility configuration.

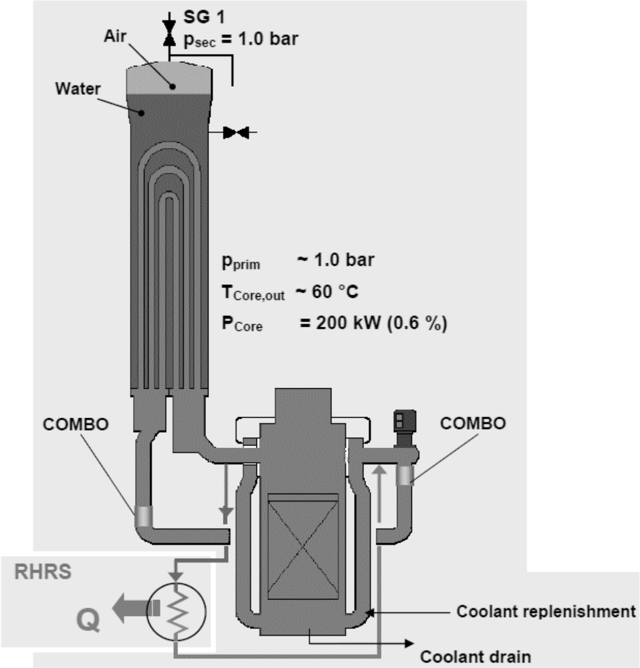

Figure 3-1 Initial (SOT, t=0) Test Facility Configuration for G1.1 Test Run

Table 3-1 Initial Conditions for Test G1.1

Primary side	
General conditions of flow and heat transfer	Cold shut-down conditions. No flow. Loops 1 filled with water up to ¾-loop, N_2 above. Remaining 3 loops isolated by blank flange close to RPV outlet/inlet. RHRS active in loop 1.
Coolant inventory	1060 kg (PRZ isolated)
Boron concentration	2000 ppm
Heater rod bundle power	200 kW
Pressure	≈ 1 bar (atmospheric pressure)
Fluid temperature at core outlet	≈ 333 K
Subcooling at core outlet	≈ 40 K
Pressurizer fluid temperature	PRZ isolated throughout the whole test
Pressurizer level	
Flow conditions	No flow
Secondary side	
Secondary pressure in SG (remaining SGs not in operation)	≈ 1 bar (atmospheric pressure), MSRV closed
Secondary temperature in SG 1	≈ 298 K
Water levels in SG 1	≈ 12.2 m (air above) 3-1

3.1.2 Tests Run Conditions

The run of test G1.1 was started at steady state conditions at SOT time scale t = 0 with the initial conditions described in the above tables (see Table 3-2 and Figure 3-2). The loop was filled at ¾ with the RHRS engaged. The test starts with the shut-down of the RHRS. As a consequence, a heat-up of core inventory is produced, starting the steam formation in the core after approximately 10 minutes after the shut-down and consequently the frothing of the core inventory.

In test G1.1 a reduction of primary coolant inventory is caused in order to establish a swell level in the SG inlet chamber below the tube sheet. This established a heat transfer mode in the U-tubes similar to RC operation, with active and passive heat transfer zones. After that reduction of the primary coolant inventory a gradual increase is carried out. Previously to the coolant inventory increase a (quasi-) steady state conditions have been establishment. During the whole test run, heat transfer to the secondary side leads to a temperature and pressure increase on the secondary side. But the secondary side of loop 1 was kept constant pressure of 2 bars and liquid level of 12.2 m, via the main steam relief valve (MSRV) and feedwater injection. The procedure returned a sequence of phases at steady-state operating conditions.

Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DC-tubes. In this way, additional coolant was injected into already subcooled fluid and not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/replenishment procedures.

In Table 3-2 there are chronologically displayed the changes of coolant inventory and significant events during test phase for the PKL III facility in the course of test G1.1. Figure 3-2 presents the evolution of the main parameters along the transient.

Table 3-2 Test run G1.1: Changes of Coolant Inventory and Significant Events

General Time [s]	Time after SOT [s]	Measures / Events	Primary coolant inventory [kg] +/- 20kg
0		Preliminary Test Phase	1060
7900	0	Start of Test (SOT)	1060
8340	440	Star of Coolant Drain with 0.219 kg/s	1060
10120	2220	End of Coolant Drain	670
23750	15850	Start of Coolant Injection with 0.06433 kg/s	670
25460	17560	End of Coolant Injection	780
27060	19160	Start of Coolant Injection with 0.0613 kg/s	780
28610	20710	End of Coolant Injection	875
34960	27060	Start of Coolant Injection with 0.06322 kg/s	875
35830	27930	End of Coolant Injection	930
45620	37720	Start of Coolant Injection with 0.0633 kg/s	930
46410	38510	End of Coolant Injection	980
49220	41320	Start of Coolant Injection with 0.06587 kg/s	980
50890	42990	End of Coolant Injection	1090
53400	45500	Start of Coolant Injection with 0.0666 kg/s	1090
53700	45800	Increase of Injection Rate to 0.1298 kg/s	1110
55010	47110	End of Coolant Injection	1280
57150	49250	Start of Coolant Drain with 0.703 kg/s	1280
57520	49620	End of Coolant Drain	1020
58890	50990	End of Test (EOT)	1020

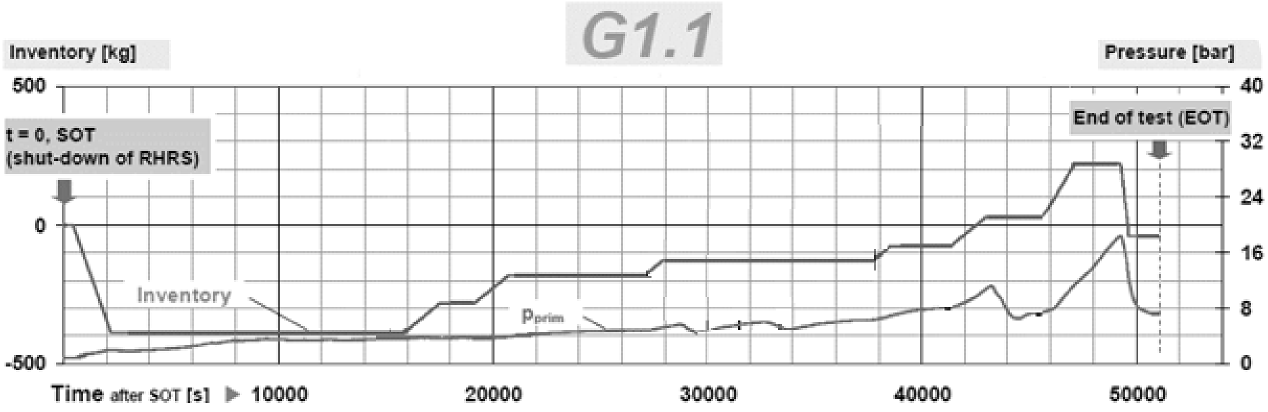

Figure 3-2 Evolution of Main Parameters (Inventory, Primary Pressure) for G1.1 Test Run

3.2 Test G1.2

3.2.1 Initial Test Conditions

The PKL III G1.2 test was conducted in the PKL facility, this test is focused in the study of the residual heat removal by two steam generators in the presence of non-condensable gases, the other two loops were isolated during test execution.

The test conditions and the initial inventory status were arranged in the course of the preliminary test phase. The preliminary test phase started with a complete filling of the entire loops 1 and 2 with subcooled water at a homogeneous boron concentration of 2000 ppm and ambient pressure (p_{prim} ~ 1 bar). The slow drain of the primary inventory down to ¾-loop (approximately 1140 kg of residual inventory) was attended by a constant feed of N_2 to the primary circuit via the PRZ valve station, thereby replacing the void volumes emerging from the drainage. The volume of N_2 fed to the primary circuit is approximately 0.8 m³ at Standard Temperature and Pressure conditions (STP) in both test runs.

After the decrease of the primary inventory, the rod bundle power was set to 200 kW (simulation of the decay heat in the core, resembling 0.6 % of full load thermal power, inclusive compensation for heat losses) and kept constant. Until start of test, the core power was removed from the primary circuit via the residual heat removal system engaging in loop 1. In the secondary side, feedwater system and main steam system were in operation for the entire duration of the test, in order to maintain pressure and water level constant.

These initial conditions were the operating ones prior to the start of test, SOT. Table 3-3 and Figure 3-3 present this test initial facility configuration.

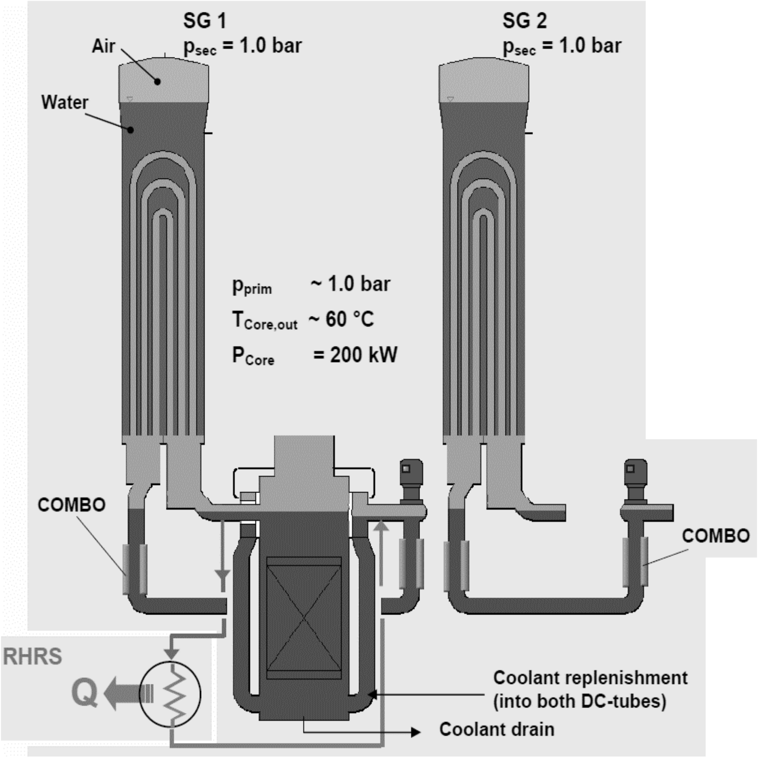

Figure 3-3 Initial (SOT, t=0) Test Facility Configuration for G1.2 Test Run

Table 3-3 Initial Conditions for Test G1.2

Primary side	
General conditions of flow and heat transfer	Cold shut-down conditions. No flow. Loops 1 & 2 filled with water up to ¾-loop, N_2 above. Remaining 2 loops isolated by blank flange close to RPV outlet/inlet. RHRS active in loop 1.
Coolant inventory	1140 kg (PRZ isolated)
Boron concentration	2000 ppm
Heater rod bundle power	200 kW
Pressure	≈ 1 bar (atmospheric pressure)
Fluid temperature at core outlet	≈ 333 K
Subcooling at core outlet	≈ 40 K
Pressurizer fluid temperature	PRZ isolated throughout the whole test
Pressurizer level	
Flow conditions	No flow
Secondary side	
Secondary pressure in SG (remaining SGs not in operation)	≈ 1 bar (atmospheric pressure), MSRV closed
Secondary temperature in SG 1	≈ 298 K
Water levels in SG 1	≈ 12.2 m (air above)

3.2.2 Tests Run Conditions

Test G1.2 was started at steady state conditions at SOT time scale t = 0 (5500 s of the general scale time) with the initial conditions described in the above tables (see Table 3-3 and Figure 3-3). The conditions just after the start of test were ¾-loops 1 and 2 filled with the RHRS still active. The test starts with the shut-down of RHRS. As a consequence a heat-up of core inventory is produced, starting the steam formation in the core after approximately 10 minutes after the shut-down and consequently the frothing of the core inventory.

The reduction of primary coolant inventory is caused in order to establish a swell level in the SG inlet chamber below the tube sheet. This established a heat transfer mode in the U-tubes similar to RC operation, with active and passive heat transfer zones. After that reduction of the primary coolant inventory a gradual increase is carried out. Previously to the coolant inventory increase a (quasi-) steady state conditions have been establishment. During the whole test run heat transfer to the secondary side leads to a temperature and pressure increase on the secondary side. But the secondary side of loops 1 and 2 were kept constant at 2 bars of pressure and 12.2 m of fill level, via the main steam relief valve (MSRV) and feed water injection. The procedure returned a sequence of phases at steady-state operating conditions.

Reduction and increase of inventory was accomplished via lower plenum drain line and injection lines into the lower section of the DC-tubes. In this way, additional coolant was injected into already subcooled fluid and not into steam volumes. Thereby, the steam condensation (and heat transfer in the U-tubes) was left undisturbed by draining/replenishment procedures.

In Table 3-4 there are chronologically displayed the changes of coolant inventory and significant events during test phase for the PKL III facility in the course of test G1.2. The evolution of the main parameters along the transient are presented in Figure 3-4.

Table 3-4 Test Run G1.2: Changes of Coolant Inventory and Significant Events

General Time [s]	Time after SOT [s]	Measures / Events	Primary coolant inventory [kg] +/- 20kg
0		Preliminary Test Phase	1140
5500	0	Start of Test (SOT)	1140
6260	760	Start of coolant drain	1140
6735	1235	End of coolant drain	980
7865	2365	Start of coolant drain	980
8175	2675	End of coolant drain	880
19520	14020	Start of coolant injection	880
20015	14515	End of coolant injection	920
26070	20570	Start of coolant injection	920
26705	21205	End of coolant injection	960
30340	24840	Start of coolant injection	960
31115	25615	End of coolant injection	1010
35125	29625	Start of coolant injection	1010
35545	30045	End of coolant injection	1035
39350	33850	Start of coolant injection	1035
39895	34395	End of coolant injection	1070
43250	37750	Start of coolant injection	1070
44800	39300	End of coolant injection	1165
50095	44595	Start of coolant injection	1165
51360	45860	End of coolant injection	1245
54570	49070	Start of coolant injection	1245
56035	50535	End of coolant injection	1340
59200	53700	End of test	1340

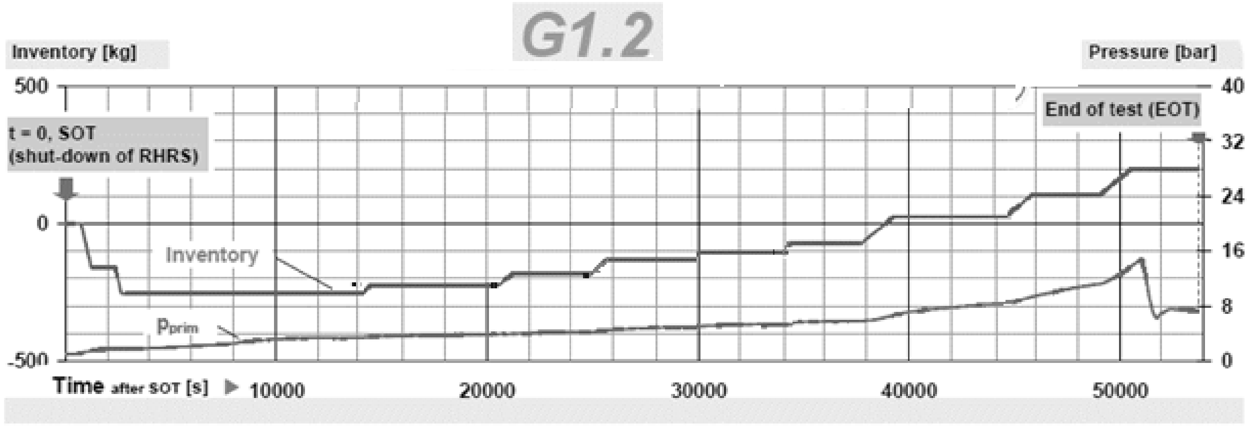

Figure 3-4 Evolution of Main Parameters (Inventory, Primary Pressure) for G1.2 Test Run

4 MODELING WITH TRACE CODE

The aim of this study is to compare the experimental measurements made at the PKL facility with the results provided by simulations of the TRACE code. With this purpose, two TRACE models have been used. On the one hand, there is a model of the own experimental PKL facility, with a 1-D vessel (i.e., the vessel has been implemented as pipes). While on the other hand, there is a model of a commercial PWR plant, with a 3-D vessel.

4.1 Conditioning Phase

The previously mentioned models, both the one of the experimental PKL facility as the one of the commercial PWR plant, were not in the initial conditions of the G1.1 and G1.2 tests. Therefore, it has been necessary to carry out a conditioning phase, in order to reach these initial experimental conditions. The procedure followed for both cases is presented throughout the next paragraphs.

4.1.1 PKL III Facility Model

The TRACE 1-D model of the PKL III E2.2 test conditions (developed by "Grupo de Análisis Dinámico de Sistemas Energéticos del Instituto de Técnicas Energéticas de la Universidad Politécnica de Cataluña") is the employed as a starting point. Therefore, first step is to deal with the evolution from E2.2 test conditions to the initial G1 test series conditions. Table 4-1 presents the main characteristics of tests E2.2 and G1.1-G1.2.

Table 4-1 E2.2 vs. G1.1-G1.2 Test Conditions

Test	E2.2	G1.1-G1.2
Primary Pressure (bar)	42	≈1
Secondary Pressure(bar)	28	≈1
Rod Bundle Power (kW)	530	≈200
Coolant Inventory (kg)	2250	1060
Boron Concentration (ppm)	1000	2000

As can be seen from Table 4-1, test conditions are quite different in E2.2 and G1 series, so thoroughgoing work has been needed to reach the initial G1.1 and G1.2 test conditions. Besides, not only the previous differences shown in Table 4-1 were present: mass flow rates, temperatures, pressures, extraction and injection events, valves adjustment, control systems and many other elements have been modeled or modified. After having achieved the initial steady state, initial G1.1 and G1.2 test conditions, the pre-test phase is ended. Test phase can begin, this phase starts with the shut-down of the RHRS, the sudden lock of the RHRS produces a quick rise of core temperature.

Along these paragraphs the main changes made in the PKL model for the test G1.1 are presented. A schematic view of the TRACE model of the PKL facility is shown in Figure 4-1. Being these changes similar to those made in the model for the G1.2 test, with the only difference that in this last case there are two active loops instead of one. Thus, changes made to the PKL model of test G1.1 were as follows: isolation of the 3 inactive loops (introduction of valves in the initial part of the hot leg and end of the cold leg); implementation of the residual heat removal system (RHRS); derating power (from 530kW to 200kW); adjustment of pressures and temperatures in the various elements; introduction of injections and extractions sequences of coolant and implementation of the various events (injection and extraction process), and so on. Similarly we proceeded to test G1.2 taking into account the differences between the two cases.

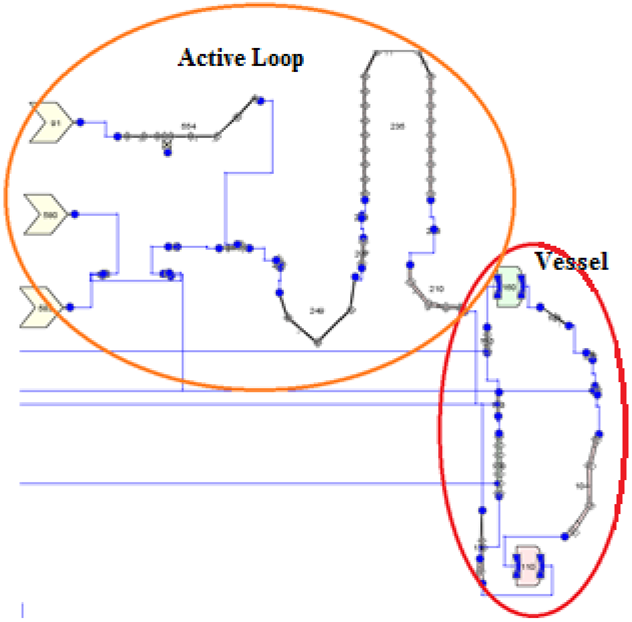

Figure 4-1 Configuration of the Primary Circuit of the PKL Facility

4.1.2 PWR Model

The configuration of the starting 3-D model of the PWR plant (Figure 4-2) is in the conditions of full load, so it should be reduced both power (from 100% to 0.6%, or what is the same from 3000MWt to about 20MWt), temperature (from about 350 to about 50°C) as the working pressure (from about 170 bars to atmospheric pressure). The primary coolant inventory was reduced until a similar level to these of the PKL facility was reached. The next step was the implementation of the residual heat removal system (RHRS), as well as the components required to have the same configuration as in G1.1 and G1.2 tests (valves, fills, breaks, etc.). Throughout the above process, it has taken into account that the PKL facility is scaled to a real plant, so that injection and extraction masses in the PWR model have been scaled too.

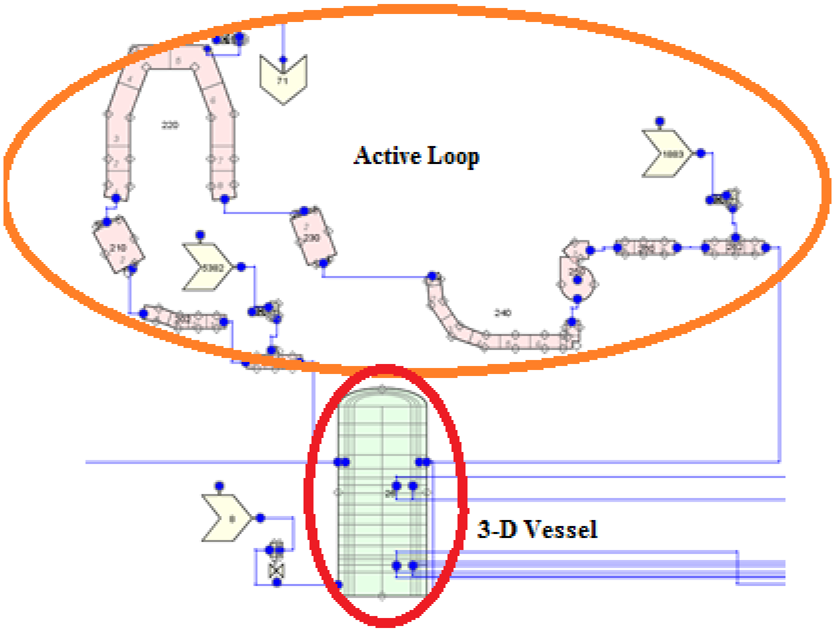

Figure 4-2 Configuration of the Primary Circuit of the PWR Plant

4.2 Steady-State Phase and Shut-Down of the RHRS

Once the initial conditions of both tests have been reached, the system is allowed to evolve under these conditions for a period of time (stationary phase prior to the test itself), in the case of test G1.1 were 7900 seconds, moment at which test G1.1 starts (point called SOT in the corresponding table). The test starts with the shut-down of the RHRS, which causes a rapid rise in the core temperature.

4.2.1 PKL III Facility Model

During the stationary phase, which precedes the test itself, because of the forced circulation caused by the RHRS, there is a thermal stratification with height throughout the core in both, PKL facility measurements and PKL TRACE model results. However, from this point on and caused by the shut-down of the RHRS, the temperature measurements of the PKL facility evolve in a different way than the experimental data. This difference is caused because the shut-down of the RHRS produces the interruption of the forced circulation, which causes the internal recirculation of the warm water. These natural circulation processes produce the subsequent homogenization of temperatures at all levels into the core (Figure 4-3), but a 1-D model is not able to reproduce this phenomenology. In the next paragraph, it is shown the procedure followed to reduce these differences and be able to represent, as far as possible, in a 1-D model this natural circulation phenomenology.

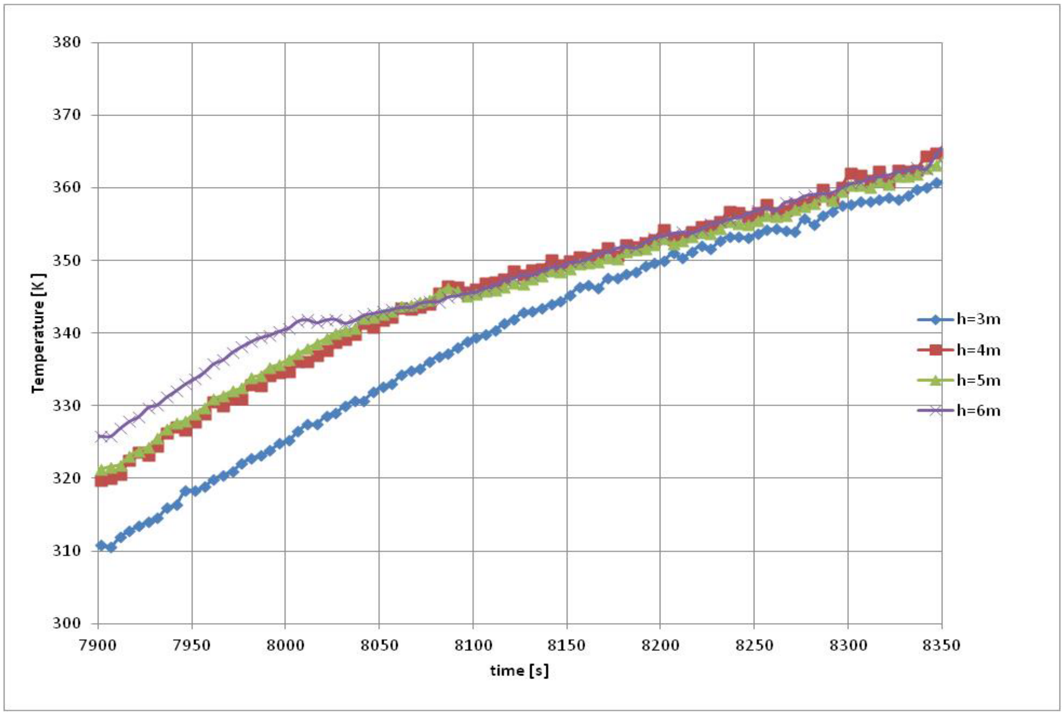

Figure 4-3 Test G1.1, Experimental PKL Core Temperature Evolution (MST 612, 574, 575 & 576 Respectively) from Shut-Down of RHRS to the First Extraction

As mentioned above, the mixing processes are not well captured by the 1-D model, because one-dimensional elements are not able to reproduce the mixing processes of natural circulation, Figure 4-4. Therefore, in order to reproduce these mixing processes due to the recirculation processes produced by the natural circulation processes, it has been necessary to implement a series of by-passes between the different elements of the core and the adjacent components, Figure 4-5 (3% of the surface flow the core pipe). Thus, it has been achieved a better mixing of the coolant inventory among the different cells which make up the core, Figure 4-6.

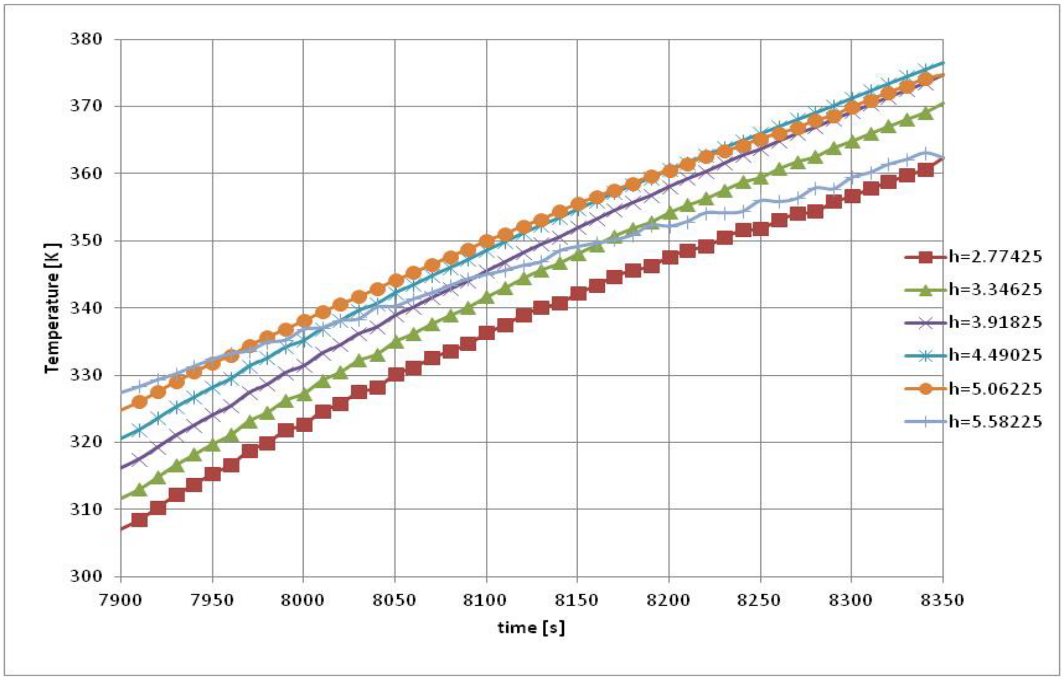

Figure 4-4 Test G1.1, TRACE Simulation Core Temperature Evolution (Pipe 120) from Shut-Down of RHRS to the First Inventory Extraction

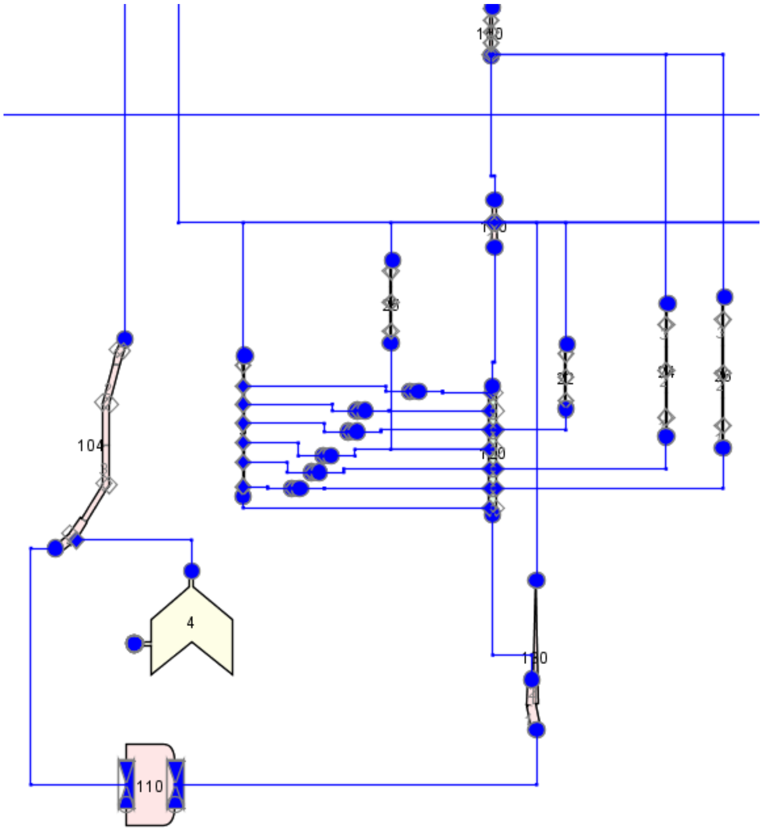

Figure 4-5 Configuration of the TRACE Model with the Auxiliary By-Passes

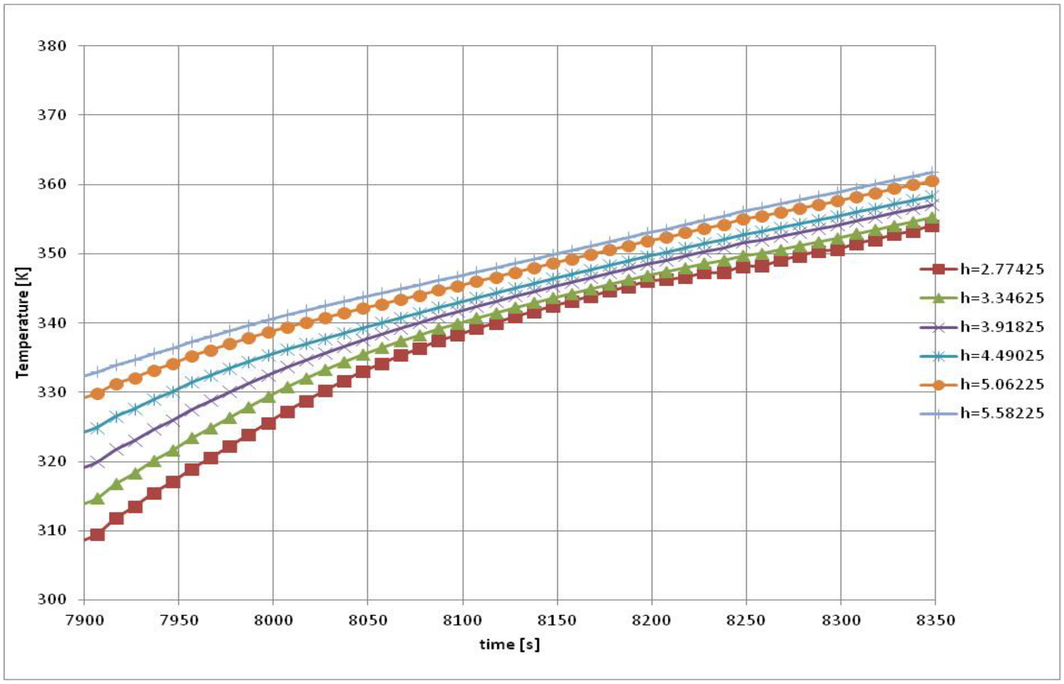

Figure 4-6 Test G1.1, TRACE Simulation Core Temperature Evolution (Pipe 120) from Shut-Down of RHRS to the First Inventory Extraction with By-Passes

4.2.2 PWR Model

The thermal stratification with elevation in the core that appeared in the previous model after the close of the RHRS is not present in this model. As explained above, this thermal stratification is due to the inability of capture the mixing processes with height in the core of the 1-D PKL model, processes which take place under natural circulation conditions. This bad coolant mixing was caused by the inability of 1-D components to simulate the mixing processes due to natural movement. This is not the case for models with a 3-D vessel, since this 3-D component has a greater capacity for the simulation of these natural circulation processes, Figure 4-7. In this figure, the TRACE results of test G1.1 for the core temperature just after the shut-down of the RHRS are shown (test G1.2 results are similar).

However, in this model has to be highlighted the decrease in the pressure of the primary circuit which takes place after having reached the initial setup. The cause of this pressure decrease is the Break shown in Figure 4-2. Its aim was to maintain constant the primary pressure, close to atmospheric pressure, during the conditioning phase to achieve the initial test conditions. Once the system is in a "stationary" state, with all parameters similar to the ones of the starting test values, we proceed to disable this element. All parameters of the model should keep approximately with constant values. But, surprisingly, this does not happen, but a decreasing from 1 to 0.25 bars during the following 10000 seconds occurs (Figure 4-8a). This decrease in pressure is due to the decrease inventory of non-condensable gases in the primary circuit (Figure 4-8b).

After making the necessary checks, it has been confirmed that a loss of mass of the non-condensable gases into the primary circuit occurs (probably caused by an internal loss of mass into the internal calculations of the code). To compensate for this loss, it has been introduced a Fill, so that the missing mass of non-condensable gases is "artificially" introduced. After some calculations and adjustments, it has been obtained that introducing a mass of about $7.5 \cdot 10^{-3}$ kg/s the pressure study is maintained around the atmospheric all over time. Thus, with the introduction of this element, the missing mass of non-condensable gases is recovered, so that the pressure remains constant up to the start of tests G1.1 and G1.2.

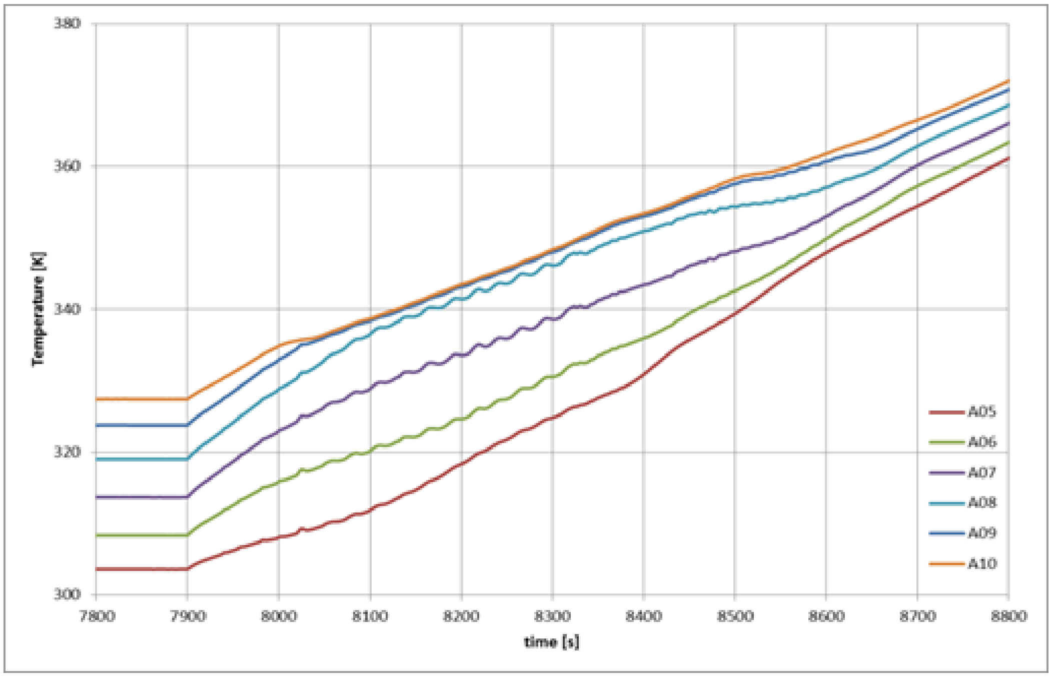

Figure 4-7 **Core Temperature Evolution from the Shut-Down of RHRS (TRACE Model of PWR Plant with 3-D Vessel)**

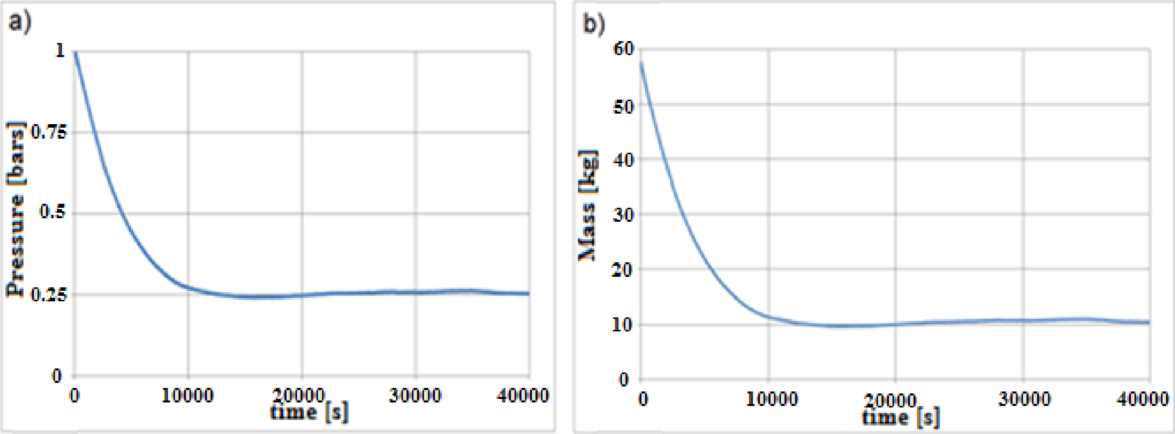

Figure 4-8 **Evolution of Primary Circuit: a) Pressure; b) Mass of Non-Condensable Gases**

5 COMPARISON OF THE EXPERIMENTAL MEASUREMENTS WITH THE TRACE SIMULATIONS

This section is devoted to review the main experimental data and to compare against the results obtained with the TRACE code for both cases, G1.1 and G1.2. Throughout the whole section, three lines are shown in the figures: the experimental data, the TRACE results for the own PKL model and TRACE results of the PWR plant.

5.1 Test G1.1

Once the initial conditions of the test G1.1 have been reached, it proceeds to launch the case with the sequence of events shown in Table 2-2. The graphs presented below show the results obtained by the TRACE code (up to the present time of simulation reached) for both the model of the experimental installation itself (PKL with all components 1-D), such as for the application to the PWR plant (with a 3-D vessel). These figures are: the collapsed liquid level and temperature in the core, the pressure in the upper plenum, the collapsed level and temperature in the steam generator and the boron concentration in the pump seal, Figures 5-1 to 5-6 respectively. Highlight that the TRACE simulation of the own PKL model reaches the end of the transient, whereas the simulation with the TRACE model of the commercial PWR plant ends abruptly around second 38000.

Regarding the collapsed level of liquid (Figure 5-1) say that the TRACE results of the own PKL model (line PKL Simul., Figure 5-1) are acceptable, although it has some differences, in addition it also has an evolution with some accused sawteeth, fact that does not happen in the experimental measurements. Regarding the simulation of a commercial plant (PWR line Simul., Figure 5-1), say that much more form-fitting results are provided by the code and also without the appearance of the previously commented sawteeth.

Going further in the analysis of the results shown in Figure 5-1 for commercial PWR plant, start by saying that the results of the simulation with the TRACE code present, in the second 7900, a slight increase in the liquid collapsed level immediately after the close of the RHRS, being similar to that measured experimentally. The next event, the strong initial extraction (reduction of coolant inventory of nearly 40% in the range from 8340 to 10120 seconds), produces a marked decrease in the level of the liquid sheet towards a value of approximately 4 meters in both cases, experimental PKL and TRACE simulation of PWR. While the subsequent recovery occurs quite differently in both cases, for the PWR simulation there is a quick rise (in less than 100 seconds) followed by a zone of almost stable level, up to the first refrigerant injection (at 23750 seconds). Whereas for the experimental PKL data there is a slow recovery of the coolant level, presenting alternating zones with increase and decrease of the coolant level, always with the upward tendency. The next event (injection between 23750 and 25460 seconds) both with an increase of the collapsed level of about one meter, although the starting point of the TRACE model is approximately half meter higher. In the interval of time from the first to the second injection (seconds 25460 to 27060) there is a small drawdown in both cases, although it is more pronounced and fast in the TRACE simulation, nearing at the end of this period of time a level very similar in both cases, around 6 meters. For the next event, the second injection (between 27060-28610 seconds), in both cases is shown an increase in the coolant level, up to about 6.5 meters. From this point on, the experimental values and those obtained from the TRACE simulation evolve in a very similar way. There is, for both cases, a slow decrease of the collapsed coolant level followed by a stabilization (time between injections, ranging from 28610 to 34960 seconds). For the following coolant injection (from 34960 to 35830 seconds), there is a very similar collapsed level of coolant inventory in both cases, although there is a slightly different evolution, the presence of peaks in the experiment against a flatter curve for the TRACE model evolution. Up to second 38000 approximately, when the sudden interruption of the TRACE simulation occurs.

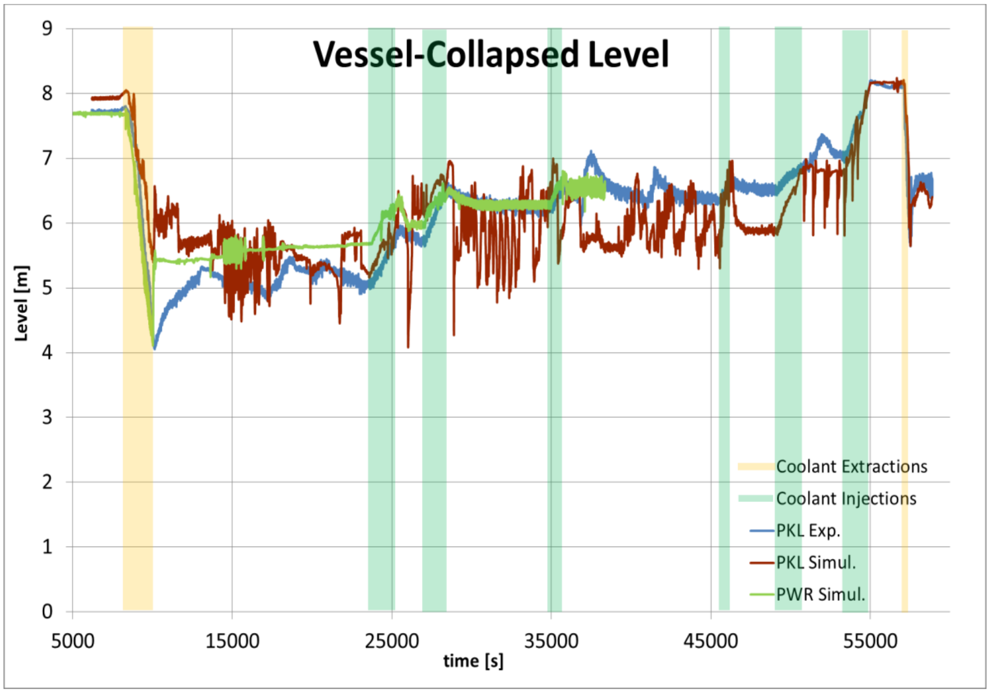

Figure 5-1 Collapsed Level of the Core for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the core temperature (Figure 5-2) say that the TRACE model of PKL (line PKL Simul., Figure 5-2) gives acceptable results, although higher values than the experimental ones in the central zone of the experiment are provided by the code, from the 15000-45000 seconds approximately. In addition it reaches a value of 450 K and here remains almost constant, although in the form of sawteeth, a fact that does not happen in the experimental measurements, in which there is an increasing tendency along the whole transient. Regarding the simulation of the PWR plant (line PWR Simul., Figure 5-2) say that follows in an accurate form the experimental values obtained in the PKL facility, although from the second 25000 approximately gives somewhat higher values, 35-40 K higher when the abrupt interruption of the TRACE simulation of the PWR plant occurs.

Going into further details on the analysis of the results of the core temperature obtained for the commercial PWR plant, we can say that experimental measurements and TRACE simulation evolve similarly for the period of time from the closing of RHRS to the strong initial extraction (between 7900 and 10120 seconds). In both cases, there is a sudden rise in temperature from 325 to about 390 K. Although, this rise in temperature is more pronounced in the experimental curve than in the PWR plant simulation results. This abrupt temperature rise is caused by the shut-down of the RHRS and it is also favored by the reduction of the coolant inventory. Towards the middle part of the extraction, there is a decrease in the slope of the increasing temperature. This situation is caused by the heat absorbed during the coolant phase change, even being able to lower the temperature towards the end of the extraction. The time between the extraction and the first coolant injection (from 10120 to 23750 second) presents an evolution quite similar in both cases. Regarding the first injection (between 23750 to 25460 seconds) say that there is no appreciable effect on the temperature. For the next interval (time between first and second injections, from 25460 to 27060 seconds), say that, while the experimental values are kept almost constant, the values of the simulation show a significant increase. Thus, from this point the evolution of the simulation and experimentally measured values are very different. While for the experimental measurement values there is a slow increase with some downfalls for the PWR plant simulation results there is a more pronounced increase without any falling. Making both temperatures increasingly move away, until the abrupt end of the TRACE transient.

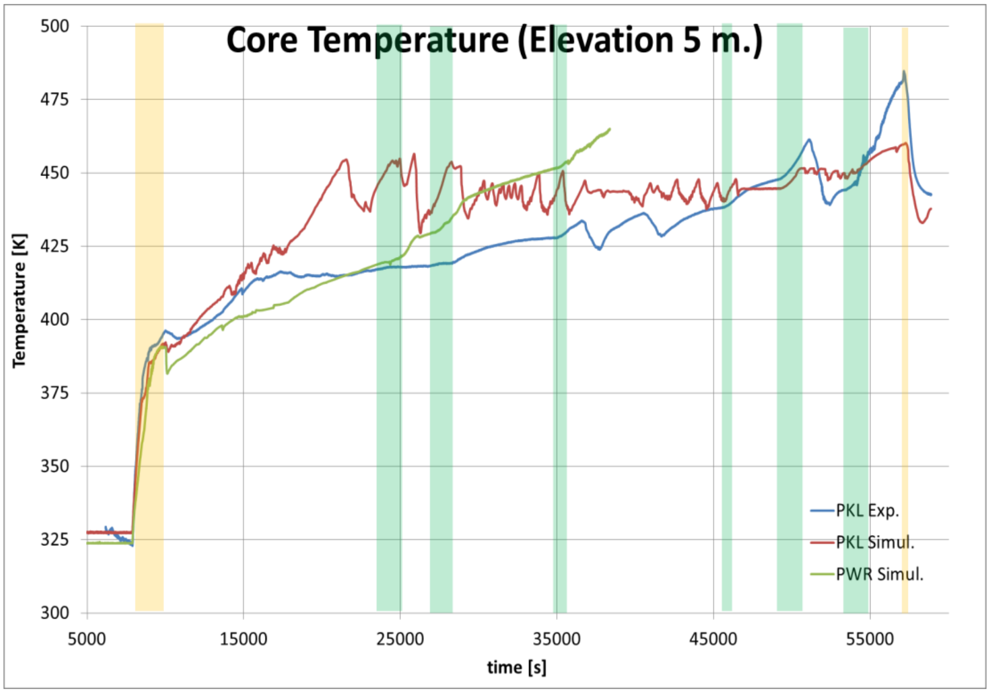

Figure 5-2 Core Temperature for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Similar comments can be made for the pressure values in the Upper Plenum (Figure 5-3). Emphasizing that, for the simulation of the PWR plant, the differences are even greater (at the end of time achieved in the simulation pressures are in the vicinity of 13 bars, while the experimental values are around 5-6 bars). Also comment the evolution in sawteeth form of the TRACE results of the own PKL facility (maximum fluctuations between about 6 and 11 bars), which does not take place in the experimental data and in the PWR plant simulation.

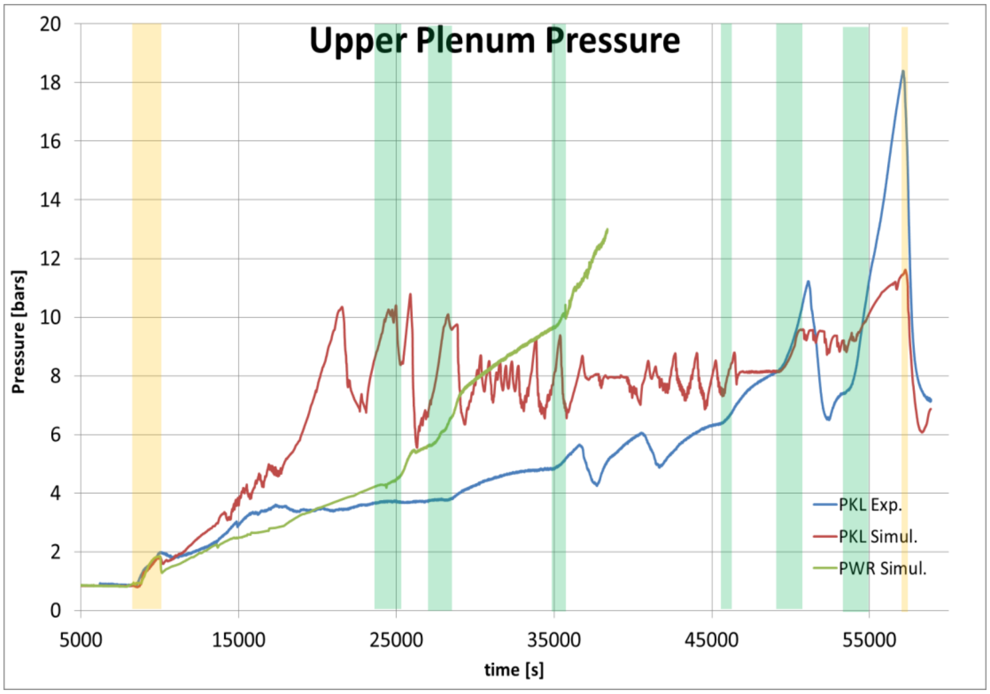

Figure 5-3 Upper Plenum Pressure for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the collapsed liquid level in the steam generator (Figure 5-4), say that for the experimental values and TRACE simulation of a commercial PWR plant the values are close to zero until second 30000 approximately. As for the model of the PKL facility begins with a sharp rise of the liquid level from about the second 8500 (middle part of the strong initial extraction of coolant inventory). Although the initial peak (about second 10500 approximately) is also present in the experimental measurements, the liquid level in the experimental measurements returns to zero in 1000 seconds approximately, whereas the PKL simulation continues is rising up to around 8 meters. From the aforementioned time, second 30000 approximately, in the experiment there is a progressive increase in the collapsed liquid level, although it evolved with sudden drops in level (specifically four until test is finished). While for the simulation of the PWR plant, there is a small level rise, just before the abrupt end of the simulation. Therefore, it is concluded that tracking of the level of liquid in the steam generator is not highly satisfactory for any of the two models, nor the own PKL model, nor the commercial PWR plant.

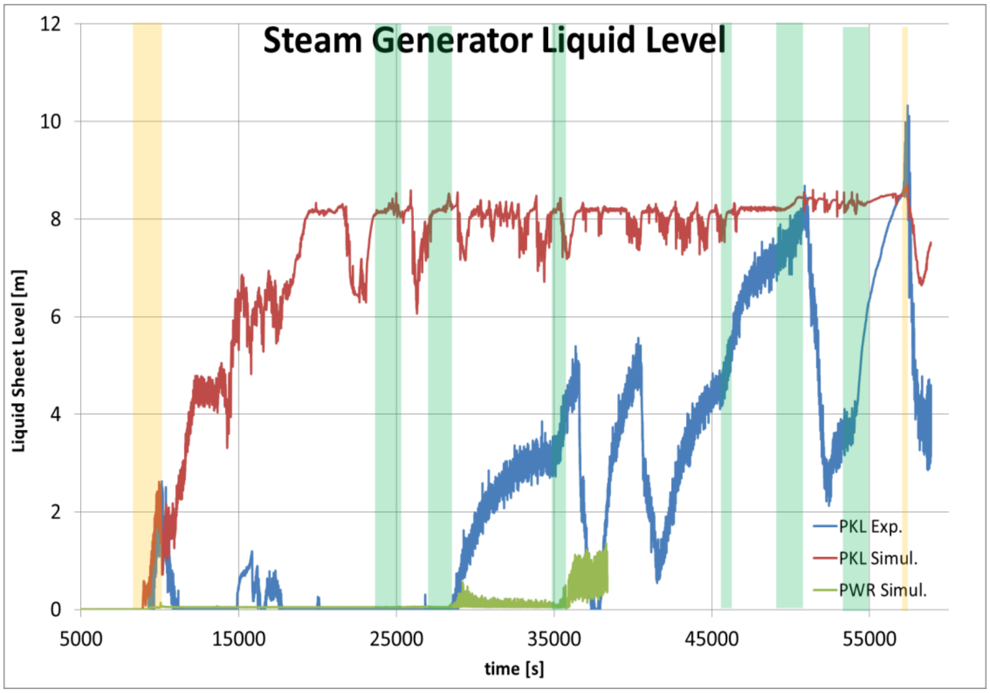

Figure 5-4 **Collapsed Liquid Level in the Steam Generator for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)**

With respect to the steam generator temperature (Figure 5-5), say that the TRACE simulation of the PKL model (line PKL Simul., Figure 5-5) has acceptable results. Although, the TRACE simulation results of the own PKL facility has lower temperature values than the experimental ones near the start of the test, from second 8000 to 15000 approximately. While, there are higher temperature values than the experimental ones in the central zone of the experiment, from second 15000 to 45000 approximately. In addition, it reaches a value of 440 K, at about 20000 seconds, remaining almost constant until the end of the transient, but in the form of sawteeth. This sawteeh form does appear neither in the experimental measurements nor in the TRACE simulations of the PWR plant. Regarding the simulation of the PWR plant (PWR line Simul., Figure 5-5), it follows accurately the form of the experimental measurement curve. While from the second 25000 approximately suffers continuous fluctuations that increase towards the end of the simulation time reached, these fluctuations also appear in the experiment, but in a lesser extent. Conclude that, without reaching longer simulation times, it can be said that the results of the TRACE simulation of a commercial PWR plant are much tighter than the 1-D model of the own experimental facility.

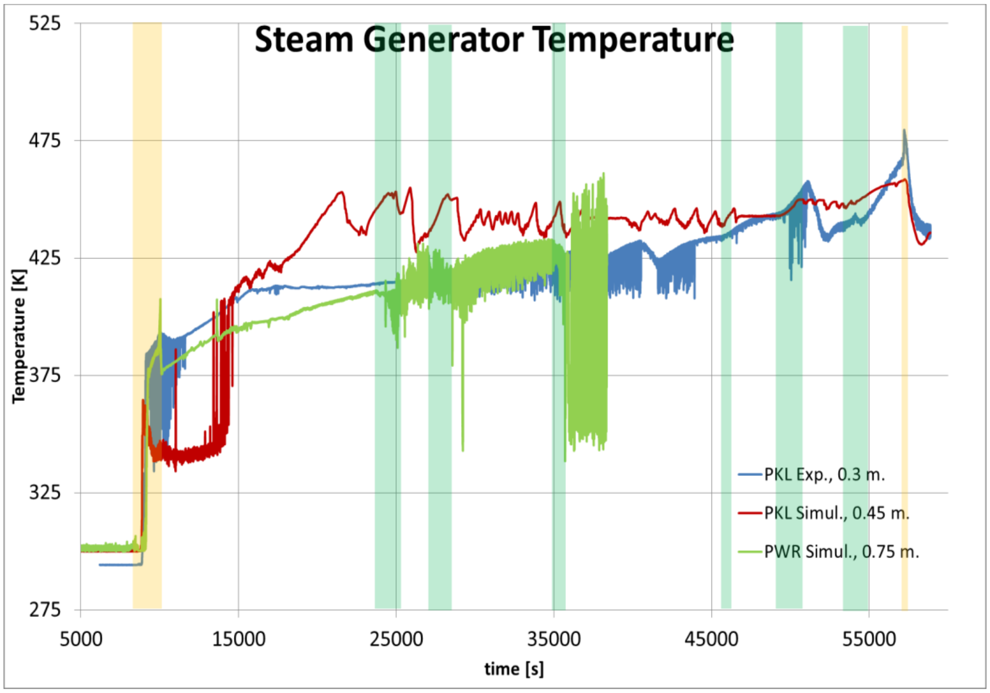

Figure 5-5 Temperature in the Steam Generator for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the boron concentration in the pump seal (Figure 5-6) say that the TRACE simulation of the PKL model (line PKL Simul., Figure 5-6) shows acceptable results, although the values obtained in the simulation are somewhat lower to the experimental values practically from the start of the test. In regard to the results obtained by the simulation with the commercial PWR plant, say that the boron concentration remains practically constant to about the second 15000, as in the experimental data. Although from this point undergoes a slight drop, up to second 25000, where immediately after the end of the first injection of coolant (between seconds 23750-25640) increases, remaining constant up to the end of second coolant injection (between seconds 27060-28610) when the boron concentration increases. Throughout this period of time the boron concentration remains constant in the experimental measurements. At about 30000 seconds of transient a decrease in the experimental measurements of the boron concentration occurs, this decreasing tendency presents sharp drops with sharp recoveries, reaching 500 ppm at second 50000 approximately. At this point, a sharp recovery which reaches the initial boron concentration occurs, stabilizing around this value until the end of test, but with a sharp decrease in the boron concentration coinciding with the primary coolant inventory extraction.

As a final comment we can say that the simulation of the test G1.1 for the commercial PWR plant has a quite good correlation with the experimental measurements up to the simulation time reached, being appreciable better than the TRACE simulations results of the 1-D model of the own PKL facility.

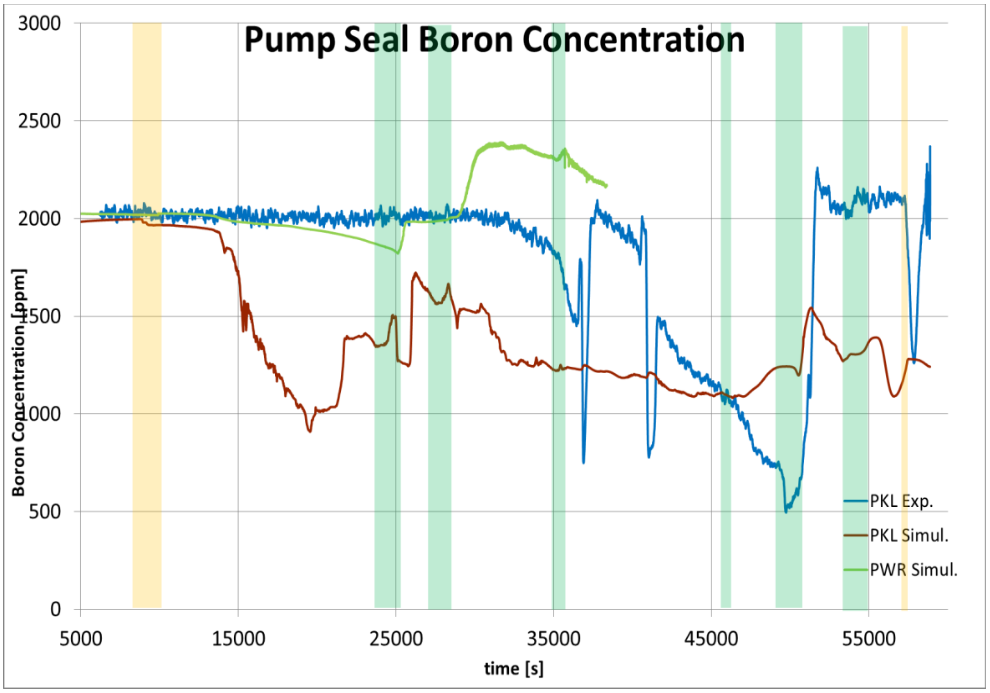

Figure 5-6 Boron Concentration in the Pump Seal for Test G1.1 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

5.2 Test G1.2

Once the initial conditions of the test G1.2 have been reached, it proceeds to launch the case with the sequence of events shown in Table 2-4. The figures presented below show the results provided by the TRACE code (up to the present time simulation) for both the model of the experimental installation itself (PKL with all components 1-D), such as for the application to the PWR plant (with a 3-D vessel). These figures are: the collapsed liquid level and temperature in the core, the pressure in the upper plenum, the collapsed level and temperature in the steam generator and the boron concentration in the pump seal, Figures 5-7 to 5-15 respectively. Highlight that both TRACE simulations end abruptly before the end of the test, near second 45000 after the begin of the transient in both cases too.

Regarding to the collapsed level of liquid in test G1.2 (Figure 5-7) say that the TRACE results of the own PKL model (line PKL Simul., Figure 5-7) are acceptable, although it has some differences with the experimental measurements, in addition it also have an evolution with some accused sawteeth, fact that does not occur in such markedly way in the experimental measurements and in the TRACE simulation of the commercial PWR plant. Regarding to the simulation of a commercial plant (PWR line Simul., Figure 5-7), say that much more form-fitting results are provided by the code, overlapping largely both data series in the figure and without the above mentioned large sawteeth form shown in the 1-D simulation of the own PKL model.

Going further in the analysis of the results shown in Figure 5-7 for commercial PWR plant, start by saying that the results of the simulation with TRACE present an evolution very similar to the experimental measurements of the PKL facility for test G1.2. After the shut-down of the RHRS (second 5500) there are in both cases, the experimental data and the TRACE simulation of the commercial PWR plant, a slight increase in the collapsed liquid level. This rise is caused by the sudden coolant warming caused by the shut-down of heat removal system. Then, the first and second extractions (seconds 6260-6735 and 7865-8175 respectively) produce a decrease in the level, below 6 meters, not reaching to leave the core uncovered as in the previous test. The decrease in level is more pronounced in the TRACE simulation of the PWR plant than in the experimental measurements. This drop is followed by a phase where water level remains practically constant, only small liquid level increases are shown, coinciding with the small coolant inventory injections (between seconds 19520-20015, 26070-26705, 30340-31115, 35125-35545 etc.). The collapsed level evolves almost equal in both cases until the abrupt end of the TRACE simulation with the model of the commercial PWR plant.

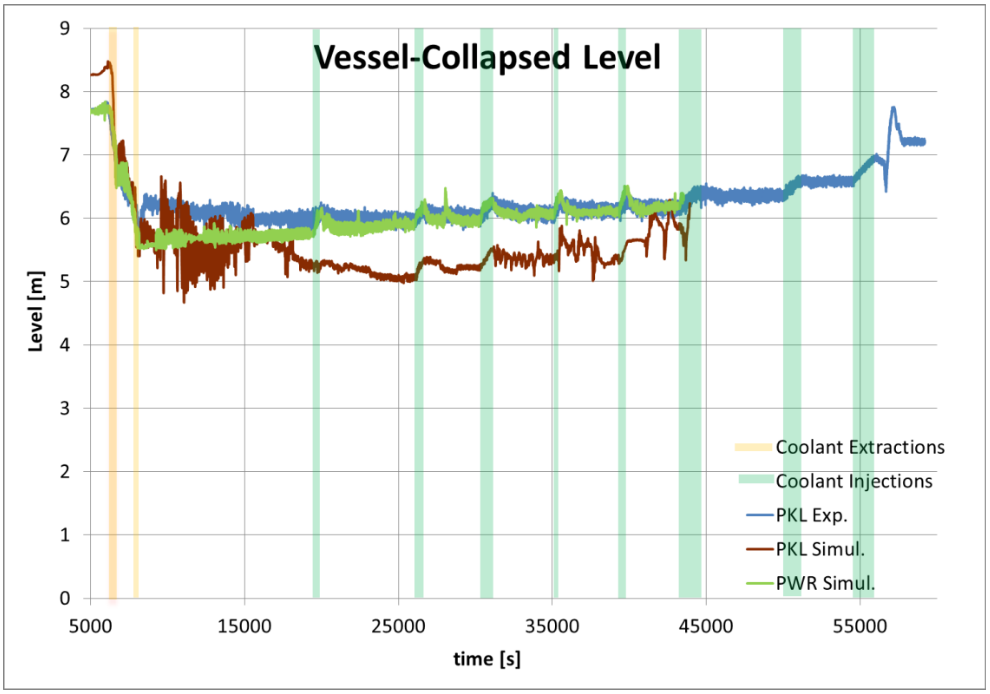

Figure 5-7 Collapsed Level of the Core for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the core temperature (Figure 5-8) say that the TRACE model of PKL (line PKL Simul., Figure 5-8) gives acceptable results, although higher than the experimental values almost during all the transient, from the 15000-45000 seconds approximately, when the TRACE simulation ends abruptly. In addition it reaches a value of 450 K and here remains almost constant, although it present an evolution in the sawteeth form, especially towards the end of the simulation. Fact that does not happen in the experimental measurements, in which there is an increasing tendency along the whole transient. Regarding the simulation of the PWR plant (line PWR Simul., Figure 5-8) say that follows in an accurate form the experimental values obtained in the PKL facility. Note that, there are temperature differences lower than 10 degrees between experimental measurements and simulation results during the entire transient, up to the abrupt end of the TRACE simulation. Conclude that TRACE results of the commercial PWR plant fit much more accurately the experimental measurements that the 1-D model of the own experimental facility.

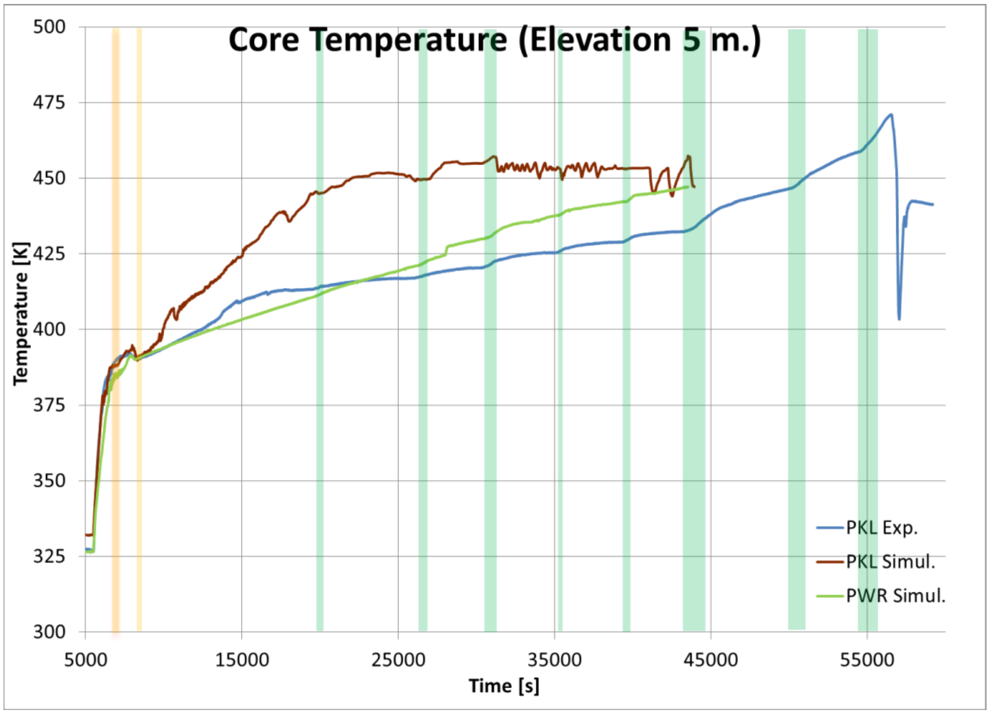

Figure 5-8 Core Temperature for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Entering in further details on the analysis of the TRACE results of the core temperature obtained for the commercial PWR plant, say that evolve similarly to the experimental measurements for the period of time from the shut-down of the RHRS until the end of the second extraction (from 6260 to 8175 seconds). In both cases, there is a sudden rise in temperature from 325 to about 390 K, although it is a little bit pronounced in the experimental curve than in the one of the simulation with the TRACE code. This abrupt temperature rise is caused by the shut-down of the RHRS and it is also favored by decrease of the coolant inventory. To the middle of this period of time, there is a decrease in the slope of the upward trend of the core temperature, this is caused by the heat absorbed during the phase change, being even able to lower the temperature to the end of the second extraction. Regarding the evolution from this point on, say that for all the coolant injections (seconds 19520-20015, 26070-26705, 30340-31115, etc.) and for all the time intervals between them, the core temperature remains with a moderate upward trend. Even though there is a slightly steeper slope in the TRACE simulation than in the experimental measurements. But, as previously mentioned, both cases have differences in the core temperatures lower than 10 K along the whole transient.

Similar comments, as made for the previous figure, can be made to the pressure values in the upper plenum (Figure 5-9). Emphasizing that, for the TRACE simulation of a PWR plant, the pressure results are somewhat greater than the experimental measurements (at the end of time achieved in the simulation pressures are around 8.5 bars, whereas the experimental values are around only 6 bars). Also mention, in addition to the higher pressure values, the sawteeth shaped evolution in the 1-D model of the own PKL facility (maximum fluctuations of about 8 to 11 bars, near the abrupt end of the simulations).

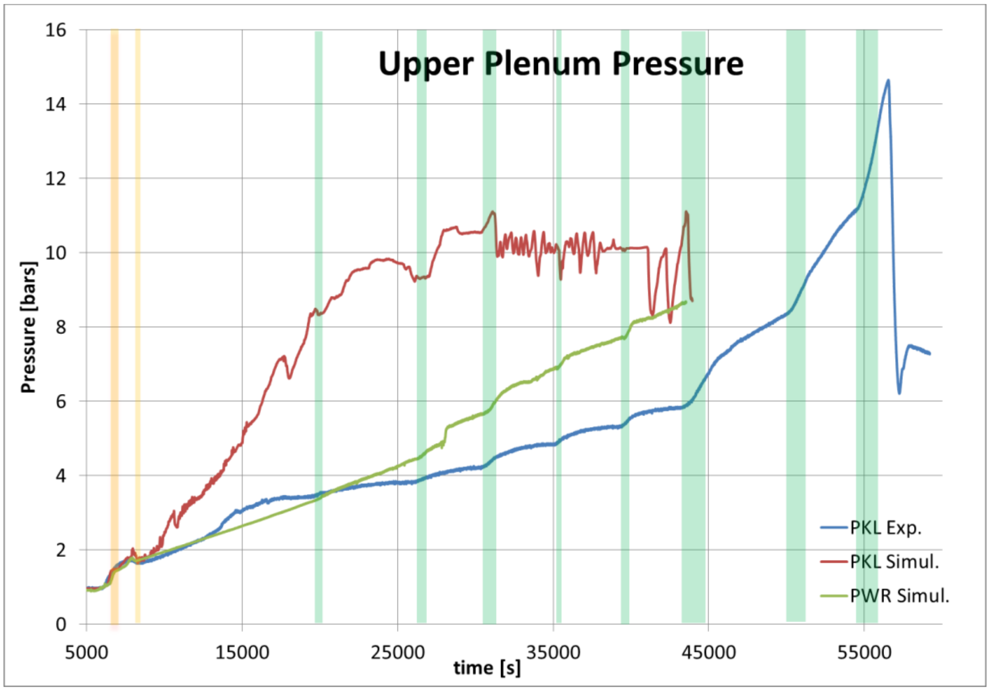

Figure 5-9 Upper Plenum Pressure for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the collapsed liquid levels in the two active steam generators (Figures 5-10 and 5-11), say that have very similar experimental values. Both experimental data series are close to zero until the second coolant injection (second 27000 approximately). From this point on, there is a progressive increase of the collapsed level, up to 9 meters towards the end of the test, ending with a sharp level drop to approximately 3 meters. TRACE simulation results of the commercial PWR plant have values close to zero throughout the simulation time reached. Whereas for the TRACE model of the PKL facility, the collapsed level begin is rise from the second 6000 approximately, continues increasing although it has an initial peak (about second 8000 approximately, from over 2 meters to about 0.5 meters coinciding with the second coolant extraction), it recovers and steadily increases up to 8 meters at second 18000 approximately. Value of the collapsed level at which stabilizes, remaining there until the abrupt end of the simulation. Therefore, it is concluded that tracking of the level of liquid in the steam generators are not highly satisfactory for any of the two models, nor the own PKL model, nor the commercial PWR plant.

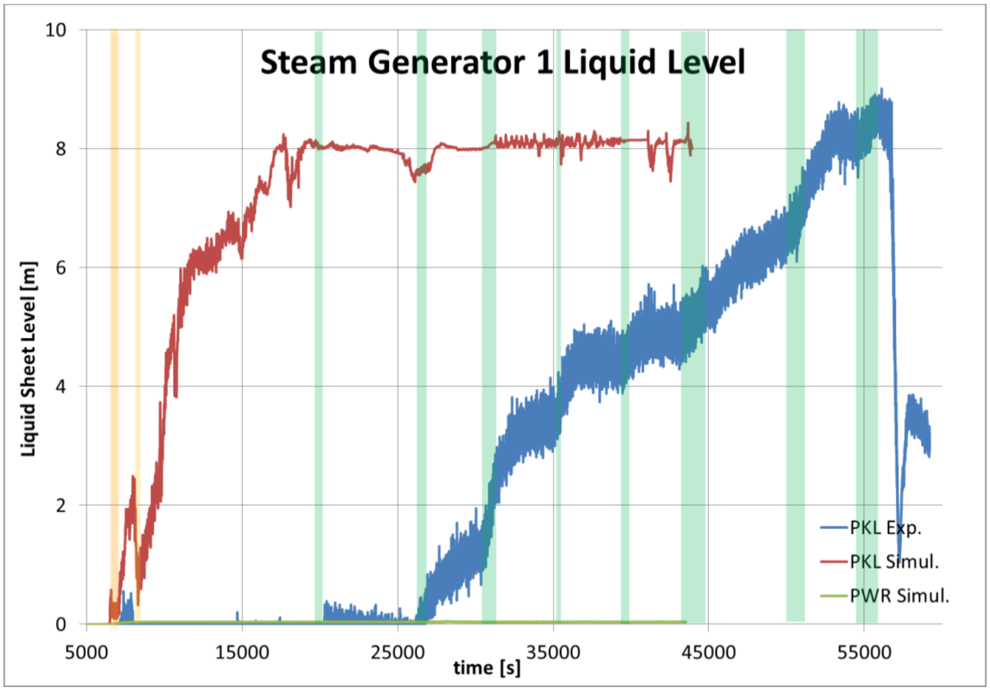

Figure 5-10 Collapsed Liquid Level in the Steam Generator 1 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

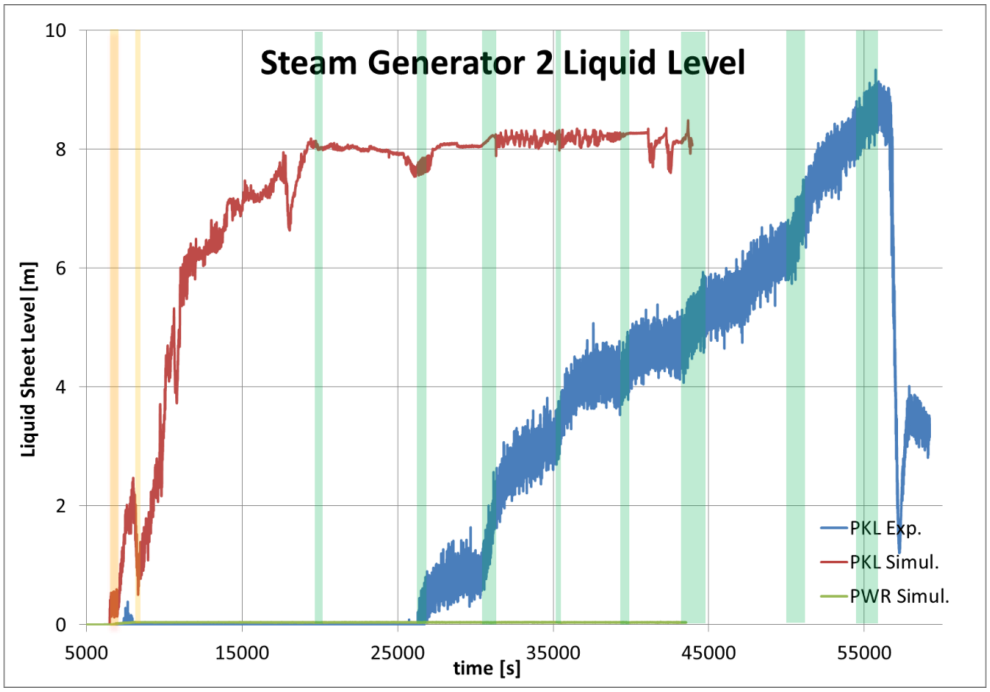

Figure 5-11 Collapsed Liquid Level in the Steam Generator 2 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

Regarding the gas temperatures in the lower part of the steam generator (Figures 5-12 and 5-13), say that the TRACE simulation of the PKL model (line PKL Simul., Figures 5-12 and 5-13) has acceptable results. Although, the TRACE simulation results of the own PKL facility has lower temperature values than the experimental ones up to second 10000 approximately. While, the TRACE simulation results of the own PKL facility have higher temperature values from second 15000 to 45000 approximately, when the TRACE simulation ends abruptly. In addition, it quickly reaches a value of 430 K, at about second 20000, remaining almost constant until the abrupt end of the simulation. Regarding the simulation of the commercial PWR plant (curve PWR Simul., Figures 5-12 and 5-13), it follows quite accurately the experimental measurement curve. The main tendencies of both cases are similar, for instance, the initial temperature increase of 75 K caused by the shut-down of the RHRS and favored by the coolant extractions, the continuous fluctuations from second 2000 up to the end of test and the continuous temperature increase during the whole transient. Conclude that, without being able to reach the end of the transient in the TRACE simulation, it can be said that the temperature results near the entrance of the steam generators of the TRACE simulation of a commercial PWR plant are much tighter to the experimental measurements than those of the 1-D model of the own PKL facility.

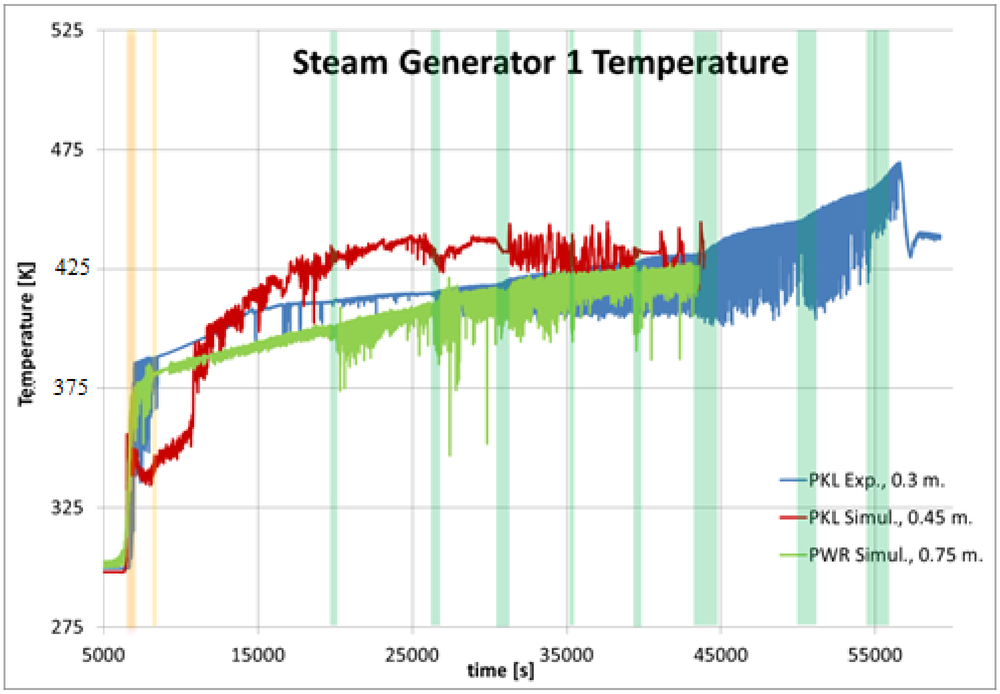

Figure 5-12 Temperature in the Steam Generator 1 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

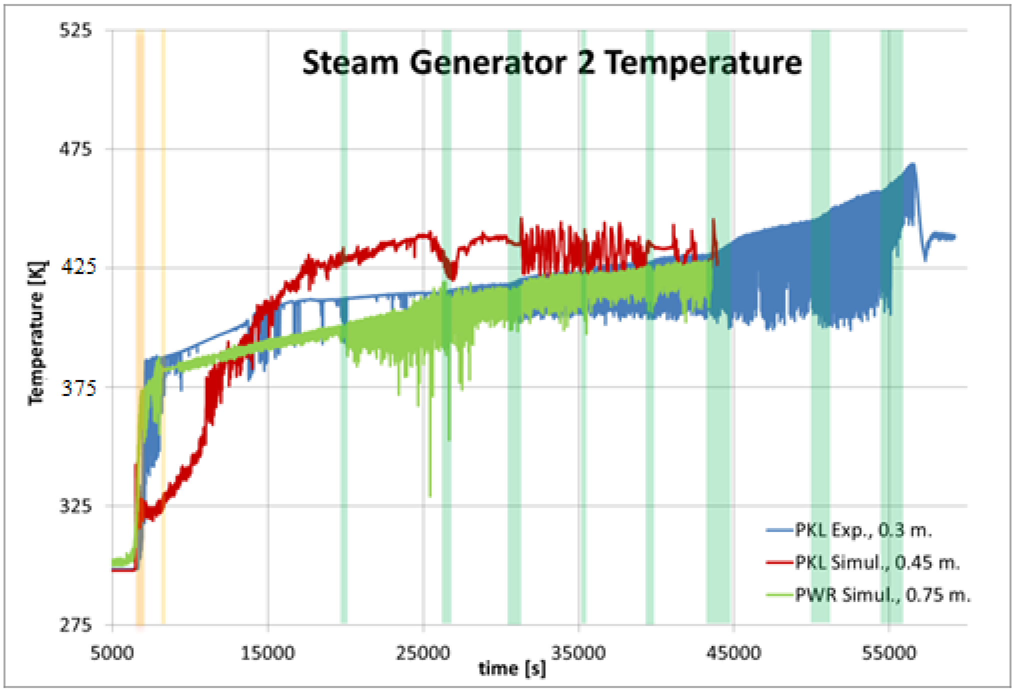

Figure 5-13 **Temperature in the Steam Generator 2 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)**

Regarding the boron concentration in the pump seal of the active loops (Figures 5-14 and 5-15) say that the TRACE simulation of the PWR model (line PWR Simul., Figures 5-14 and 5-15) shows acceptable results. Although the results obtained in the simulation are somewhat lower to the experimental values from the start of the test, this is due to the fact that the experimental boron concentration data are somewhat higher to theoretically ones reported in the reports of the test. In regard to the results provided by the simulation of own PKL facility, say that the boron concentration of the 1-D model of the PKL facility (line PKL Simul., Figures 5-14 y 5-15) are lower than the experimental ones during all the transient. In addition, the TRACE results also present a fall near the second 11000, this decrease in the boron concentration only takes place in this simulation. For the PKL experimental data and for the TRACE simulation results of the PWR plant there is a constant boron concentration until the second 30000 approximately. Although from this point, the experimental measurements show a continuous decrease in the boron concentration, from 2200 to 1000 ppm approximately (between 30000 and 45000 seconds), being practically equal in both steam generators. While for the TRACE simulation results of the PWR plant, there is a slight increase in the boron concentration, slightly differing from one generator to the other. At the abrupt end of the TRACE simulation, the values of the boron concentration are about 2250 and 2750 ppm, for steam generators 1 and 2 respectively. Finish this analysis of boron concentrations in the steam generators saying that the results for the TRACE simulation of the commercial PWR plant are appreciably better than those provided by the model of the own PKL facility during the first 30000 seconds, not being accurate from this point none of the two simulations.

As a final comment we can say that the TRACE simulation of the test G1.2 for the commercial PWR plant model has a quite good correlation with the experimental measurements up to the simulation time reached, being appreciable better than the TRACE simulations results of the 1-D model of the own PKL facility.

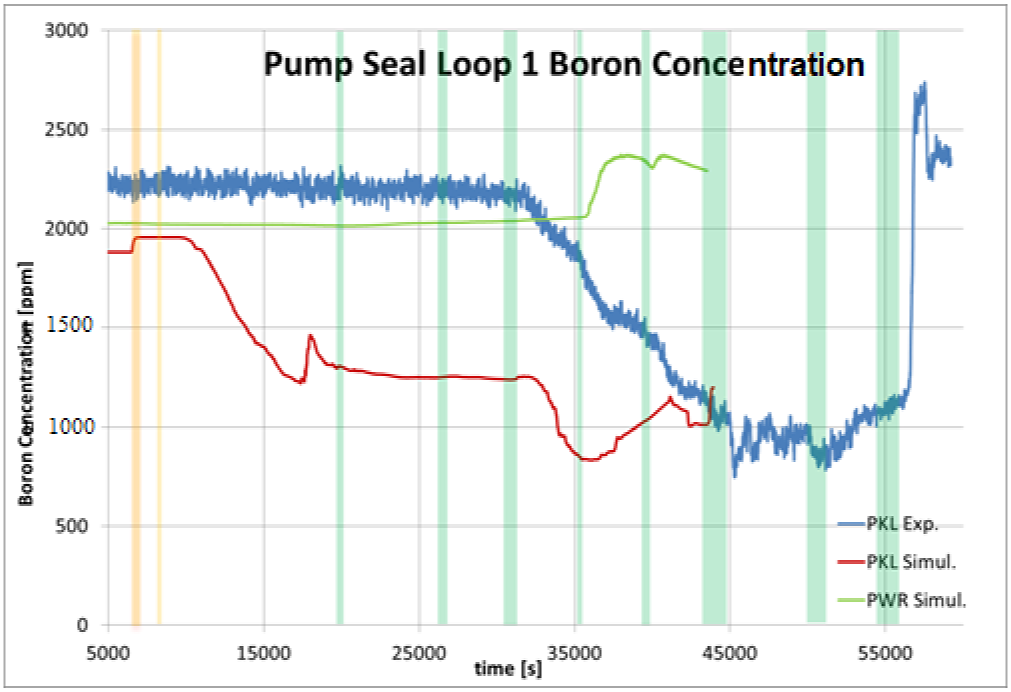

Figure 5-14 Boron Concentration in the Pump Seal of Loop 1 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

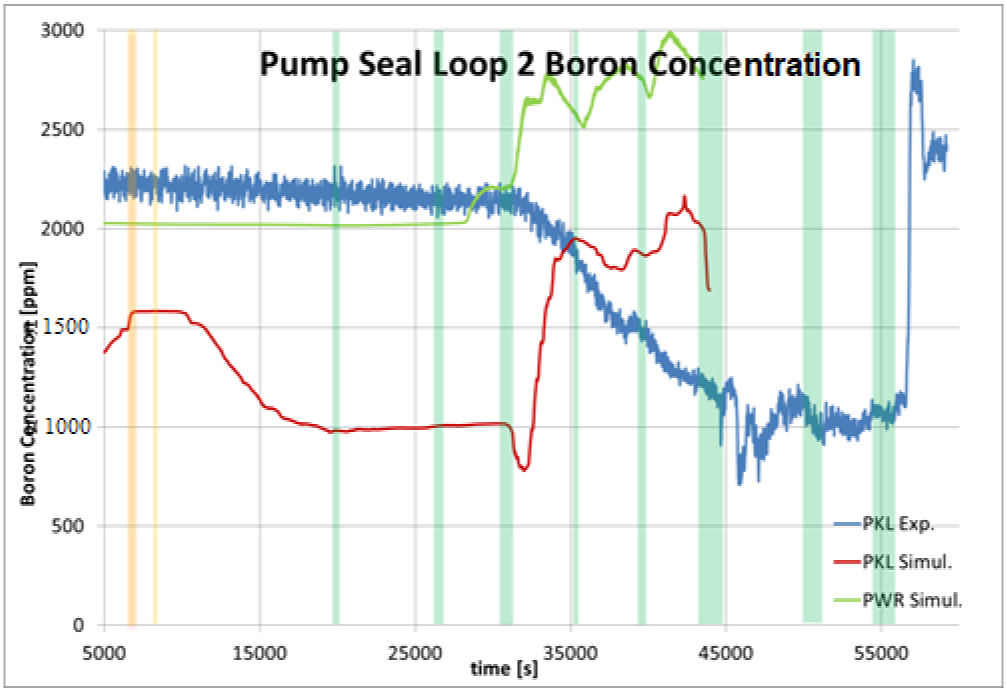

Figure 5-15 Boron Concentration in the Pump Seal of Loop 2 for Test G1.2 (Experimental PKL Data, TRACE Results of PKL and TRACE Results of Commercial PWR Plant)

6 CONCLUSIONS

The PKL III test facility simulates a typical 1300 MWe pressurized water reactor of Siemens / KWU design. In G1.1 and G1.2 tests run, the primary coolant inventory was at 3/4-loop level, this level corresponds to the elevation of the inlet and outlet of the hot and cold legs respectively. Thus, the heat transfer mechanism in the steam generator in presence of nitrogen, steam and water as a function of the primary coolant inventory in single and double loop operation (tests G1.1 and G1.2 respectively) has been investigated.

In this document, a post-test analysis of PKL III G1.1 and G1.1a tests run using TRACE code, Version 5.0, has been shown, concentrating in the TRACE simulations results of a commercial PWR plant. The comparison with the experimental measurements, carried out in the PKL facility, and the results provided by the TRACE code for a model of the own PKL facility are also discussed. Also being commented the changes that have been made in both TRACE models to meet the initial conditions of the experimental tests, exposing the problems that have appeared in this process of adaptation and during the transient simulations.

The comparison of the PKL experimental measurements and the results provided by the TRACE model, for both the model of a commercial PWR plant (with a 3-D vessel) and the model of own PKL facility (model with 1-D components), have been analysed throughout this document. Highlight the clear superiority shown by the model with a 3-D vessel, when reproducing the experimentally measured values. While, in general, it can be said that satisfactory results have been obtained with both TRACE models, even though the 1-D model provides a more distant results to the experimental data compared with the ones of the 3-D vessel model. Also highlight the wider amplitude of the fluctuations in several magnitudes that appear in the one-dimensional model, versus a more linear evolution of the experimental values and the simulation results with a 3-D vessel model. While, it should be analysed in depth the problem that causes the loss of mass detected in the non-condensable gases for the 3-D vessel model (compensated by introducing a small injection of mass). Concluding and stressing that 1-D elements of PKL model are not suitable for the simulation of experiments in which processes of natural circulation are important, being more convenient to use models with 3-D vessels, as used in the case of application to a commercial PWR plant. Highlighting, as the most important gap in both models, the little reproducibility of the collapsed liquid levels of the steam generators, which could affect other variables.

As a final conclusion, say that the satisfactory results with the TRACE code have been obtained for the majority of the studied magnitudes, thereby contributing to the code improvement and to the design of new tests. Also highlight the superior capability of the 3-D model of a commercial PWR plant against the 1-D model of the own PKL facility in simulating the experimental measurements of the tests. But not even with the 3-D vessel of the plant model the results are as accurate of desirable. Consequently, is not enough to have 3-D components, then probably the code should had be programmed with at least a simple turbulence model and with the possibility to implement a finest meshing of the different components, mainly those of the core region, in order to be able to capture the evolution of these natural circulation processes. Added to this predominance of the long-term natural circulation processes, boron dilution and diffusion processes are also present, which lead to significant differences between experimental data and simulation results, probably mainly caused by turbulence phenomena. Consequently, the current document confirms the difficulties that TRACE code has in simulating these long-term experiments in which forced circulation has no longer importance, these huge difficulties are common to all thermal-hydraulic codes. In addition, a so extremely long transient, with almost sixty thousand seconds, and which evolves under natural circulation and diffusion processes are beyond the initial objectives of TRACE design. But, despite the very high difficulty of this transient simulation, at the same time, this simulation is useful to find and explore the calculation limits of the different TRACE code versions. In particular, this document mainly explores the capacity of TRACE V5.0 patch 2 to reproduce natural circulation processes in two long-term transients, displaying the code behaviour beyond the design limits of the code, as TRACE was not intended originally to capture this turbulence phenomenon.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)

The main goal of this report is to explain a PWR plant application of the G1 tests series carried out in the PKL III facility through a TRACE model. With this purpose, the experimental data and TRACE V5.0p2 simulation results of PKL III G1.1 and G1.2 tests are used. Then, two TRACE simulations have been carried out, one for a commercial NPP model and the other for a own PKL facility model. The PKL III G1 test series are focused on the occurrence of boron dilution processes following the loss of RHRS during ¾-loop operation. Test G1.1 features a systematic study on heat transfer in SG U-tubes in presence of nitrogen, steam and water with variable Primary Coolant Inventory (PCI) in the PKL III test facility with a single loop configuration. While G1.2 test as the same purpose than G1.1 but with two loops in operation. A goal of this report is to analyse the capacity of TRACE V5.0p2 code to precisely simulate thermal stratification and natural circulation of both single and two-phase flow inside the whole primary circuit of PKL facility.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

TRACE Code; PKL Facility; G1 test series; Steam Generator; Heat Transfer Mechanisms; Presence of Nitrogen, Steam and Water; Dependency with Coolant Inventory; Single Loop Operation; Double Loop Operation; Plant Application.

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